



Transverse mixing of transported material in simple and complex stream reaches

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Abstract

Stream ecologists often make assumptions about the extent to which transported materials (such as dissolved nutrients, particulate organic matter and pollutants) are mixed across the width of a channel. Transverse spatial heterogeneity arises whenever material enters the channel at a point or restricted source, and is dissipated downstream as mixing evens out concentration gradients. A frequent assumption is that the distance required for complete mixing is negligibly short, and therefore that transverse heterogeneity in transported material is not to be expected. However, few mixing data are available for small (discharge <5 m³/s) channels. We measured mixing distances in three small (0.04–0.1 m³/s) eastern Iowa streams via mid-channel injections of a fluorescent tracer. Mixing distances varied, with effectively complete mixing (to statistically undetectable heterogeneity in tracer concentration) taking as little as 5 m or as much as 100⁺ m. Mixing was more rapid in more complex stream reaches and across constrictions and pools (vs. simpler channels). These mixing distances are not negligible when compared to typical spatial scales for ecological experiments.

Introduction

The importance of spatial and temporal heterogeneity in structuring ecological systems is firmly established (e.g. Kolasa & Pickett, 1991). The dramatic spatial heterogeneity of lotic systems in particular has long been recognized (Hynes, 1970), and aquatic ecologists have increasingly incorporated this heterogeneity into their understanding of ecological patterns and processes in streams and rivers (Palmer & Poff, 1997). Lotic systems display heterogeneity at all spatial scales (Downes et al., 1993; Palmer et al., 1997; Stevenson, 1997) from differences among basins to differences across the surface of a single cobble. Heterogeneity at both coarse and fine scales is well documented for a wide range of abiotic and biotic variables (Hynes, 1970; Downes et al., 1993; Allan, 1995; Palmer et al., 1997) including light, temperature, depth, flow, substrate and benthos. Heterogeneity is also possible in quantity of transported material

(gases, nutrients and pollutants in solution, and inorganic and organic particles in suspension). For small rivers and streams, however, interest in this possibility has generally been limited to the reach scale and above because of the presumption that rapid mixing in small channels removes fine-scale heterogeneity very quickly (e.g. Hynes, 1970; Ciborowski & Craig, 1989; Allan, 1995; Fonseca & Hart, 1996). Surprisingly, though, data testing this presumption are few.

Local heterogeneity in transported materials arises when dissolved or suspended material is introduced into the channel at a spatially restricted (narrow) source, and is dissipated as mixing evens out concentration gradients downstream. The physical mechanism for mixing involves molecular diffusion, turbulent diffusion, and advection (for an introduction to the fluid dynamics of mixing, see Rutherford 1994). Mixing has transverse (cross-channel), longitudinal (along-channel), and vertical components, but we focus on transverse mixing because of its potential to

influence environmental heterogeneity on scales relevant to benthic stream organisms. Longitudinal mixing is primarily of interest when inputs are pulsed (in which case it determines the sharpness of concentration peaks passing over the streambed); we studied mixing of a constant-flow input instead because we suspect that most interesting natural and experimental material inputs are persistent enough for longitudinal heterogeneity to be much weaker than transverse heterogeneity. Similarly, we ignored vertical mixing because in shallow streams like ours, vertical mixing is extremely rapid relative to transverse mixing (Rutherford, 1994, S.B. Heard, pers. obs.).

Transverse heterogeneity in transported materials, once established, will persist for some finite distance – the mixing distance – downstream. How fast is transverse mixing in small streams, and are mixing distances really negligible? That they are not always negligible is evident from the fact that strong transverse heterogeneity can exist in natural streams (Hardwick et al., 1995; Dent, 1999). There is an extensive engineering literature on the fluid dynamics of mixing in open channels (reviewed in Fischer et al., 1979; Rutherford, 1994), but a satisfactory general treatment remains elusive. Furthermore, both theoretical and empirical studies have mostly been concerned with large rivers, with interest motivated largely by the need to predict mixing downstream of effluent outfalls (Osborne & Davies, 1987; Milne et al., 1993; Rutherford, 1994). Transverse mixing in the largest rivers can take as much as 1,000 km (e.g. Dolgoff, 1929 in Hynes, 1970). Smaller rivers and streams will certainly mix more rapidly, but beyond this qualitative expectation almost nothing is known about mixing rates in small channels (very roughly, for discharge $<5 \text{ m}^3/\text{s}$; Fischer et al., 1979; Rutherford, 1994). Our ignorance of mixing distances in streams is troubling, because the rate at which mixing removes heterogeneity in transported material is of potential importance for two general classes of reasons.

First, knowledge of mixing rates may be critical for the design of sampling schemes and experiments in streams. For instance, schemes for sampling water quality (Sanders, 1979), suspended sediments (Beschta, 1996), invertebrates in drift (Mathooko & Mavuti, 1992) or floating exuviae (Wilson & Bright, 1973) will not accurately represent the stream unless they take into account cross-channel heterogeneity (Hardwick et al., 1995). Many experiments rely on the achievement of complete mixing: for instance, estimates of spiralling lengths (Webster & Ehrman 1996),

nutrient enrichments via drip addition (Peterson et al., 1993, Pringle & Triska, 1996, Mulholland et al., 2000), stream discharge measurements via tracer dilution (Hersch, 1985), or studies of pollutant transport (Reckhow et al., 1989). Other experimental designs, in contrast, rely on incomplete mixing: for instance, the use of side-by-side control and manipulated levels of transported material such as fish odor (McIntosh et al., 1999) or organic particles (S.B. Heard et al., unpublished data).

Second, spatial pattern in levels of transported toxicants or resources can lead to spatial patterns in species performance or community structure. For instance, where pollutants enter channels from effluent pipes or tributaries, effects on biota can be spatially restricted (Clayton & Menendez, 1996); this problem may be especially acute when toxic precipitates are formed during mixing (Weatherley et al., 1991; Poléo et al., 1994). Natural materials in transport will show similar heterogeneity during mixing if they arise from restricted sources. Of particular interest for stream communities may be spatial heterogeneity in levels of dissolved nutrients (Dent 1999) and of fine particulate organic matter (FPOM, the food source for collecting stream invertebrates). Both dissolved nutrients and FPOM may be introduced locally to a stream at confluences, in runoff where drainage rills enter a permanent channel, or from local concentrations of parent organic material (Heard & Richardson, 1995; Pringle & Triska, 1996). Wherever mixing is incomplete, microhabitats across the breadth of a channel can vary in quality for stream organisms. At a community level, spatial heterogeneity in abiotic conditions tends to foster biodiversity in streams and other habitats (Rosenzweig, 1995; Downes et al., 1998; Minshall & Robinson, 1998). The rate of mixing, together with the availability of restricted sources will determine the extent and scale of spatial heterogeneity in the concentration of transported materials.

We studied the transverse mixing of transported material in three small (discharge $0.04\text{--}0.1 \text{ m}^3/\text{s}$) eastern Iowa streams. We had two major goals. First, we sought to measure transverse mixing distances in our streams, with a view to identifying the approximate spatial scales on which stream ecologists might expect mixing to be important. Second, we sought to associate patterns in mixing distances across reaches or streams with features of channel morphology. By channel morphology, we mean physical features of a channel (such as depth, breadth, sinuosity, and the

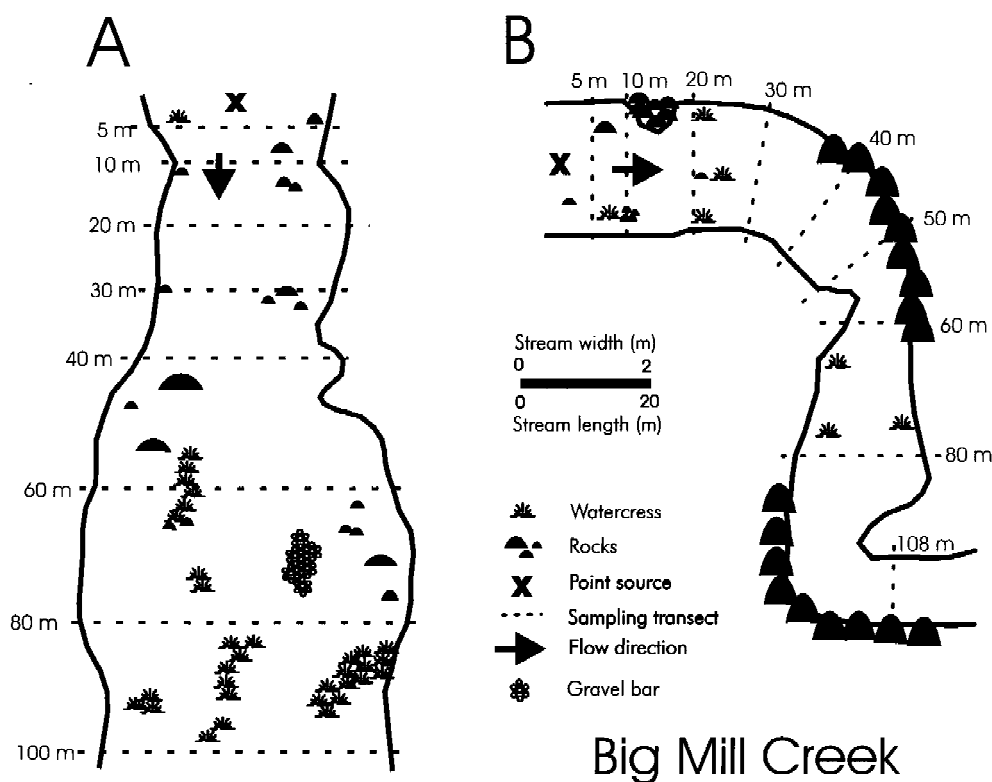


Figure 1. Study reaches in Big Mill Creek. Note 10-fold reduction in map scale along length of reach compared to width. The 0.1 and 1 m sampling transects are omitted for clarity. (A) Simple reach. (B) Complex reach.

presence of obstructions) that might affect water flow and therefore the rate of mixing.

Methods

We studied mixing in three small streams in eastern Iowa, U.S.A.: Big Mill Creek, Mossy Glen Creek and Bear Creek. All three are second-order streams flowing through partly to fully forested valleys, and all three have substantial springwater input. Big Mill Creek (near Bellevue, Iowa; 42°17' N, 90°32' W) has a typical baseflow of 0.04 m³/s and a limestone pebble/cobble substrate. Mossy Glen Creek (in Mossy Glen State Preserve near Strawberry Point, Iowa; 42°42' N, 91°25' W) has a baseflow of approximately 0.08 m³/s and a mixed substrate of limestone pebble/cobble and clay. Bear Creek (in Bixby State Preserve, near Edgewood, Iowa; 42°41' N, 91°24' W) has baseflow about 0.1 m³/s and a substrate of limestone cobble with occasional boulders.

We conducted a total of 12 mixing experiments (Table 1). Six of these (#1–#6) contrasted mixing in

simple and complex stream reaches: in each stream, we chose a pair of ≈100 m reaches to represent the continuum from simple to complex channel morphologies. The simpler reach (Figs 1A, 2A and 3A) in each case was approximately straight and was mostly riffle with only moderate variation in width and depth. The more complex reaches (Figs 1B, 2B and 3B) varied in depth from about 5 to 50 cm, and included pools, constrictions, large debris, sharp turns, and in one case water input from a pond outflow. The remaining six experiments (#7a–#8c, all in Big Mill Creek) measured mixing across constrictions and pools (channel features we thought likely to influence mixing). We identified three constrictions where the bulk of the flow was restricted to 1/3 or less of the surrounding channel width, and three pools where the channel was deep and flow very slow. We compared reaches of clearly different morphologies (simple, complex, pool, constriction), but did not attempt detailed measurements of morphology within reach types because even a complete quantitative representation of morphology does not permit theoretical prediction of mixing rates (see *Channel morphology* in **Discussion**).

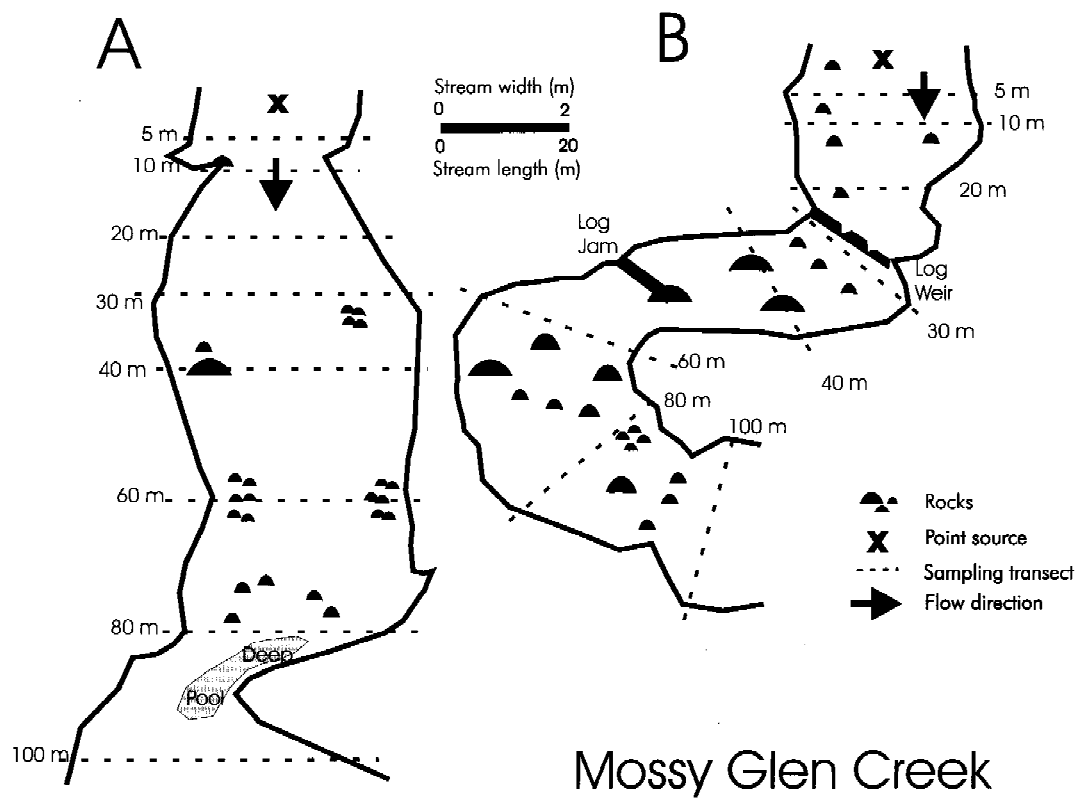


Figure 2. Study reaches in Mossy Glen Creek. Note 10-fold reduction in map scale along length of reach compared to width. The 0.1 and 1 m sampling transects are omitted for clarity. (A) Simple reach. (B) Complex reach.

Table 1. Summary of experimental designs

Experiment ^a	Stream	Type of reach/feature	Sampling stations ^b	Map
1	Big Mill	simple reach	0.1, 1, 5, 10, 20, 30, 40, 60, 80, 108	Figure 1A
2	Big Mill	complex reach	0.1, 1, 5, 10, 20, 30, 40, 46, 60, 80, 100	Figure 1B
3	Mossy Glen	simple reach	0.1, 1, 5, 10, 20, 30, 40, 60, 80, 100	Figure 2A
4	Mossy Glen	complex reach	0.1, 1, 5, 10, 20, 30, 40, 60, 80, 100	Figure 2B
5	Bear	simple reach	0.1, 1, 5, 10, 20, 30, 40, 60, 80, 100	Figure 3A
6	Bear	complex reach	0.1, 1, 5, 10, 20, 30, 40, 50, 60	Figure 3B
7a	Big Mill	pool	1, 10	–
7b	Big Mill	pool	1, 10	–
7c	Big Mill	pool	1, 10	–
8a	Big Mill	constriction	1, 7	–
8b	Big Mill	constriction	1, 8	–
8c	Big Mill	constriction	1, 13	–

^aDates: Experiment 1, 7/9/97; 2, 9/13/97; 3–4, 3/29/99; 5–6, 4/12/99; 7–8, 11/15/97.

^bLocation of stations, in m downstream from tracer source.

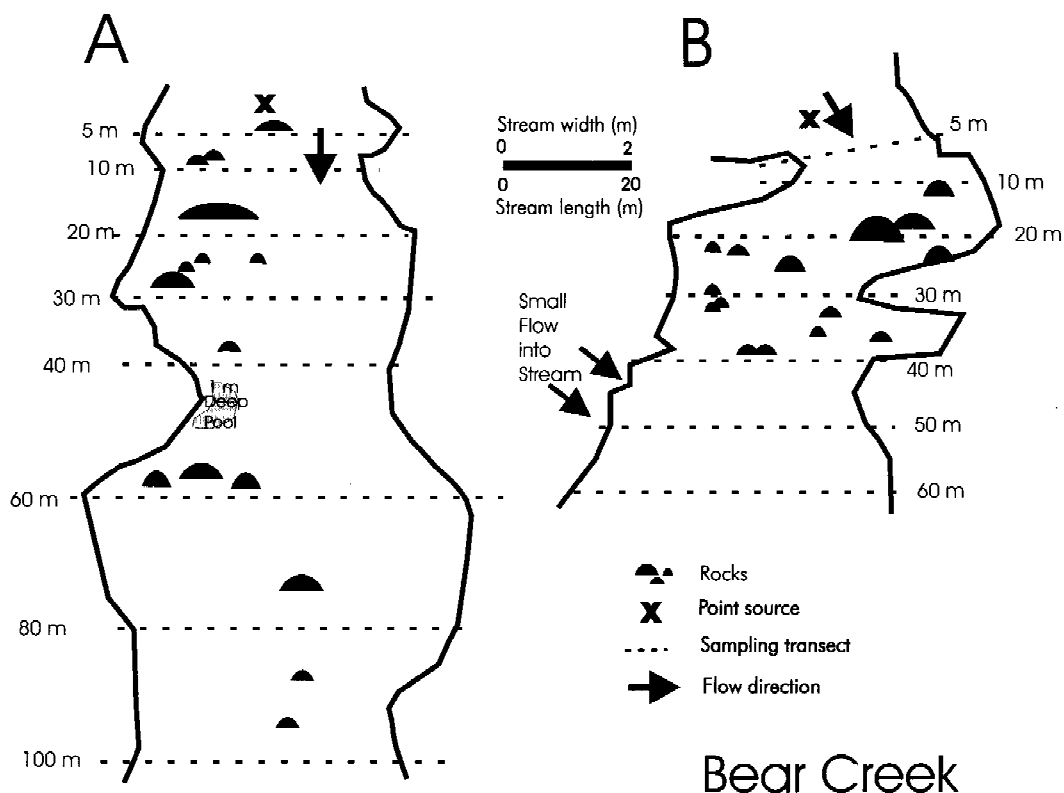


Figure 3. Study reaches in Bear Creek. Note 10-fold reduction in map scale along length of reach compared to width. The 0.1 and 1 m sampling transects are omitted for clarity. (A) Simple reach. (B) Complex reach.

Our mixing experiments shared a 4-step basic design: we (1) introduced a fluorescent tracer into the stream at a mid-channel source, (2) collected water samples across the breadth of the channel at transects downstream from the tracer introduction, (3) assayed tracer in each water sample, and (4) measured mixing by analyzing the distribution of tracer across each sampling transect.

Introducing tracer

We used a water-soluble fluorescent dye (8 g/l Rhodamine WT [Formulab, Piqua, OH] in distilled water) as a tracer. The dye solution was continuously stirred and pumped into the stream (at 3.3 ml/min by a peristaltic pump) at an introduction point in the middle of the channel, just below the water surface. We added tracer at a single restricted source (the outlet of a length of 3 mm i.d. PVC tubing) for two reasons: first, near-point addition is the simplest possibility and a logical starting-point for the study of mixing in small streams; and second, similar additions are common in ecological experiments adding materials to streams

(e.g. Peterson et al., 1993; Pringle & Triska, 1996). Future studies measuring mixing from less tightly restricted sources would certainly be valuable.

Most data indicate that Rhodamine behaves as a conservative tracer over km-scale stream and river reaches (Cushing et al., 1993; Milne et al., 1993). Bencala et al. (1983), however, reported moderate dye sorption over a 300 m reach of a shallow stream with extremely slow flow (3.5 cm/s, about 15-fold slower than any of our streams). While we did not test for tracer conservation, none of our conclusions would be affected even by substantial dye losses along our study reaches.

Before adopting the soluble dye as a tracer, we ran a pilot experiment comparing mixing between the dye and a luminescent powder slurry (powder #1162R, BioQuip, Gardena, CA). The powder consists of angular particles resembling in size FPOM naturally entrained in the stream. Powder and dye mixed in the stream at very similar rates, and in subsequent experiments we used only the dye tracer because it was much easier to handle and assay.

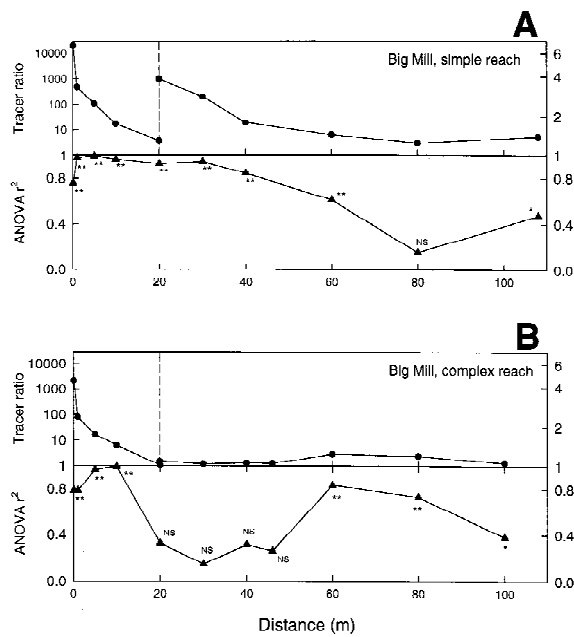


Figure 4. Mixing in Big Mill Creek. (A) Simple reach; see Figure 1A. (B) Complex reach; see Figure 1B. Distance is measured from the point of introduction of the tracer dye. Tracer ratio: ratio of highest to lowest average concentration of tracer dye among the five sampling points across the stream width. Note the vertical scale change at the dashed line (20 m distance). ANOVA r^2 : fraction of variance in dye concentration explained by sampling point, using the five samples from each of the five sampling points (r^2 from one-way ANOVA). Double asterisk, $P < 0.001$; single asterisk, $P < 0.01$; NS, $P > 0.01$.

Sampling

After waiting for the tracer plume to extend through the entire study reach (usually 30–60 min), we began sampling. We established transverse sampling transects at various distances (0.1–108 m, Table 1) downstream of the tracer source. At each transect, we took 5 simultaneous water samples at points equally spaced across the width of the channel. For each sample, a 20 ml plastic syringe (without needle) was filled at 4 ml/s. We began sampling at the downstream end of the reach and worked up to the tracer source, to minimize disturbance to natural flow patterns. After sampling all transects once, we waited for debris to be flushed from the reach and natural flow patterns to be re-established, and then began sampling again at the bottom of the reach. We repeated this procedure until we had five replicate samples for each sampling point at each transect. Samples were stored in the dark at 4°C pending analysis.

When transported material is incompletely mixed, the concentration at any point will vary through time

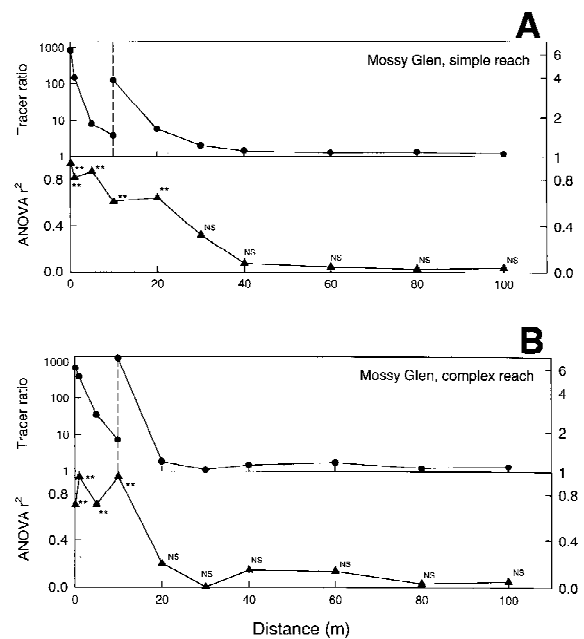


Figure 5. Mixing in Mossy Glen Creek. (A) Simple reach; see Figure 2A. (B) Complex reach; see Figure 2B. Axes as in Figure 4. For tracer ratio, note the vertical scale change at the dashed line (10 m distance).

as the plume of mixing material moves in lateral currents and eddies (Rutherford, 1994). In small streams, this variation occurs over time scales of seconds to minutes (S.B. Heard et al., unpublished data). We were not primarily interested in temporal heterogeneity on these scales, because most benthic stream organisms (especially periphyton cells and relatively sedentary benthic invertebrates) will have residence times in one spot long enough to integrate over temporal variation arising from moving plumes of mixing material. Therefore, we took our replicate samples across much longer time scales, ensuring statistical independence of replicate data points and providing estimates of local temporal variation (variance among our five samples at each sampling point) as benchmarks to assess the statistical significance of apparent spatial variation (see *Statistical analysis* in **Methods**).

Sample analysis

We assayed a 3 ml aliquot from each water sample by reading fluorescence (excitation 555 nm, emission 575 nm) on a Hitachi F-4500 fluorometer. We read fluorescence of our most concentrated samples (mid-channel, 0.1 m from dye source) after a series of 10-fold dilutions, but all data shown are corrected for these dilutions.

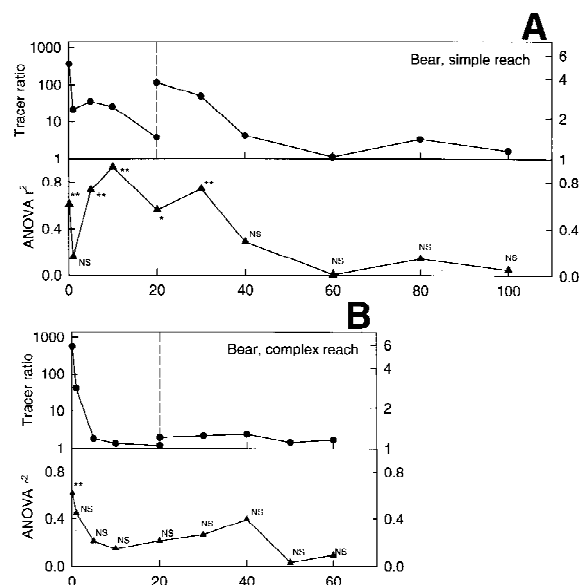


Figure 6. Mixing in Bear Creek. (A) Simple reach; see Figure 3A. (B) Complex reach; see Figure 3B. Axes as in Figure 4. For tracer ratio, note the vertical scale change at the dashed line (20 m distance).

Statistical analysis

We quantified the extent of mixing at each sampling transect using two measures, each of which is expected to decrease as mixing proceeds. First, we calculated a ‘tracer ratio’, defined as the ratio of the highest to the lowest average tracer concentrations among the 5 sampling points (1.0 in a perfectly mixed stream). We used average concentrations (over the five replicate samples) to avoid statistical problems associated with the estimation of extreme values. The tracer ratio is a standard measure of transverse mixing (Rutherford, 1994); however, instead of calculating the distance required to achieve a set tracer ratio (conventionally denoted L_z ; Rutherford, 1994, pg. 119) we report instead the actual tracer ratios at set distances. Second, we determined the model r^2 of a one-way analysis of variance (ANOVA) conducted on the 25 fluorescence readings (5 replicates for each of 5 sampling points across the stream width). This r^2 measures the proportion of overall variance in tracer concentration explained by location across the transect, and can be thought of as measuring spatial heterogeneity among sampling points relative to temporal heterogeneity (and sampling error) within sampling points. With perfect mixing, $r^2 = 0$.

Both r^2 and the tracer ratio tended to overestimate the extent of mixing (both measures are too small) for

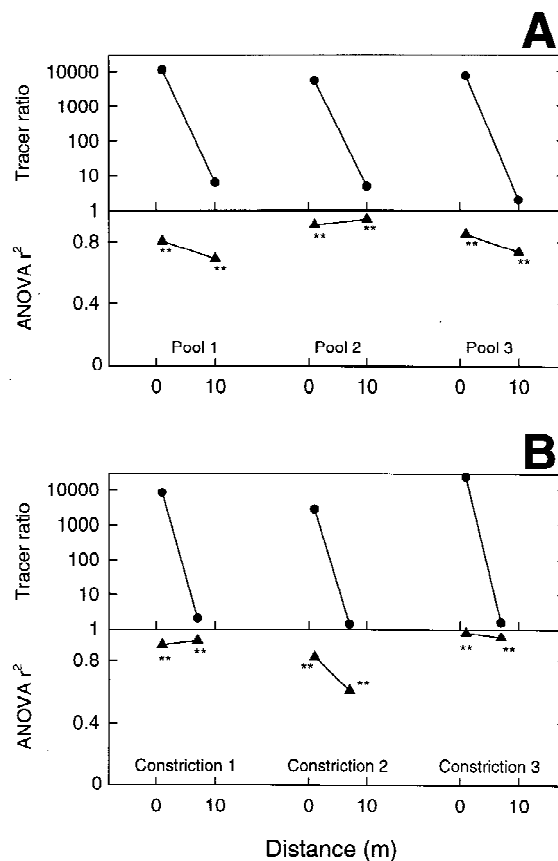


Figure 7. Mixing across pools (A) and constrictions (B) in Big Mill Creek. Axes as in Figure 4.

the transects closest to the tracer introduction (0.1 m and 1 m; see for instance left-most triangles in Fig. 4A, B). This is because the tracer plume at those transects was very narrow and in constant lateral motion, so samples drawn at the center sampling point included variable amounts of water from outside the plume (see Rutherford, 1994, pg. 20). Our conclusions are not affected by this complication.

We compared mixing between the three simple and three complex reaches using one-tailed paired t -tests on mixing (both measures) at the 20 m transect. This transect was far enough from the tracer addition to allow reliable measurement of mixing, and for complex reaches to include some of the channel features that made them complex (Figs 1–3) but not so far that mixing was complete in every reach. The 30 m transect, which also met these conditions, yielded nearly identical results; and all transects between 5 and 40 m produced comparisons consistent in direction. We used one-tailed tests because we had an *a priori*

hypothesis that mixing would be more rapid in the complex reaches. All statistical tests were performed using PC-SAS Version 7.0 (SAS Institute Inc., Cary, NC).

Results

In all six simple and complex reaches the tracer ratio declined in approximately exponential fashion as mixing progressed (Figs 4–6), with two apparent exceptions. In Big Mill Creek's complex reach (Fig. 4B) the reappearance of spatial pattern at 60 m resulted from the addition at one bank of tracer-free water from a pond. In Bear Creek's simple reach (Fig. 6A), the tracer ratio was low at the 1.0 m transect because the central sampling point happened to be in the tracer plume for only one of the five replicates (data not shown). Neither of these complications affects in any way the interpretation of our results. The ANOVA r^2 measure of mixing gave a similar picture of mixing, although with somewhat more variation overlain on the longitudinal decline.

Mixing was faster in our complex reaches than in the corresponding simple reaches. The difference was consistent for both measures of mixing and statistically significant for ANOVA r^2 despite our small sample size of three streams (paired t -tests: ANOVA r^2 at 20 m, $t = 6.4$, d.f. = 2, $P = 0.01$; tracer ratio $t = 2.6$, d.f. = 2, $P = 0.06$). In all three complex reaches, mixing was essentially complete by the 20 m transect (Figs 4B–6B); in Bear Creek's complex reach (Fig. 6B), mixing was essentially complete after only 5 m (all tracer ratios < 1.2, all $r^2 < 0.33$, NS). In the simple reaches, statistically significant pattern in tracer concentration persisted farther downstream: in Mossy Glen Creek, pattern remained at 20 m (Fig. 5A); in Bear Creek, at 30 m (Fig. 6A); and in Big Mill Creek, spatial pattern was still strong at 60 m (Fig. 4A, ANOVA $r^2 = 0.61$) and evident even at 108 m. As expected, mixing through either pools (10 m lengths) or constrictions (7–13 m lengths) at Big Mill Creek was much more complete than comparable lengths of the simple reach (compare Fig. 7 to Fig. 4A).

Discussion

Stream mixing lengths are not always negligible

Our results are the only available measurements of

mixing distances in small streams. The only study within an order of magnitude in discharge is Cotton & West's (1980) study of a straight, brick-bottomed urban stream with discharge 0.3–0.75 m³/s (but their study reach lacked the bed roughness and channel complexity possessed by most natural streams). Among larger watercourses, estimates of mixing lengths are available for channels ranging from small rivers (e.g. Grand River, 10 m³/s, Lau & Krishnapan, 1981) to enormous ones (e.g. Orinoco River, 40 000 m³/s, Stallard 1987) with mixing lengths in the kilometers to thousands of km (Dolgoff, 1929 in Hynes, 1970, Fischer et al., 1979; Rutherford, 1994). That mixing lengths are shorter in small streams has not been in doubt, but until now no direct estimates of how much shorter have been available.

Our data show mixing lengths on the order of 20–100+ m for the small (discharge 0.04–0.1 m³/s) streams we studied, with mixing faster in complex reaches (see *Channel morphology...* in **Discussion**). These estimates are conservative, because we injected our tracer in mid-channel; mixing is slower for sources closer to either bank (Rutherford, 1994). Are these mixing lengths negligible? For many purposes, clearly they are not.

Our mixing distances are long enough to exceed the spatial scales on which many stream experiments manipulate or measure stream communities (Resh & Rosenberg, 1989). These small-scale experiments reflect interest in how species abundance and community structure are spatially patterned at within-reach and smaller scales (e.g. Dudgeon, 1982; Downes et al., 1993; Crowl et al., 1997; Stevenson, 1997). Such patterns may arise from a great variety of processes, but heterogeneity in transported materials (including dissolved nutrients and toxicants and suspended organic particles) is a plausible contributor. Of course, the importance of mixing depends on the existence and importance of spatially restricted sources of transported materials in natural streams.

The design of stream experiments often makes assumptions about mixing: for instance, in a fish-odour experiment McIntosh et al. (1999) assumed a lack of transverse mixing for about 3.5 m, while in contrast a study of invertebrate drift (Lancaster et al., 1996) corrected for net-shadows by assuming complete mixing after just 1 m. In general, studies that rely on drip additions to rivers and streams (e.g. Peterson et al., 1993) assume complete mixing between the addition point and sampling stations downstream. While mixing can be accelerated by the use of diffusers and multi-point

introductions, near-point sources appear to be the most common method of addition. These additions are often made into constrictions or other features thought to encourage rapid mixing (e.g. Mulholland et al., 2000), but actual mixing distances are rarely reported. Finally, attempts to measure parameters such as discharge and mean velocity via transported tracers will fail unless tracer is sampled downstream of its complete transverse mixing. Our data suggest that the mixing distance may be surprisingly large in some streams, and (again) this distance is rarely reported even in studies strongly dependent on the mixing assumption.

We recognize one important caveat in our discussion of mixing: the rate of mixing will matter only for materials introduced into a stream at a spatially restricted source. For experimentally introduced materials, this is the rule, and our results (using a near-point dye introduction) apply directly. On the other hand, for naturally introduced materials (such as organic particles and nutrients), stream ecologists have not quantified the frequency or importance of spatially restricted sources. We suspect this is because the common presumption that mixing distances in streams are negligibly short (e.g. Hynes, 1970; Ciborowski & Craig, 1989; Allan, 1995; Fonseca & Hart, 1996) has dampened interest in the search for restricted sources. Our results show that mixing distances are often *not* negligible, and so the search for restricted sources of natural materials can and should begin.

Channel morphology and predictive models of stream mixing

Must mixing distances always be measured empirically, or might they be predictable from knowledge of stream characteristics such as velocity, discharge, and channel morphology? Unfortunately, the theory of transverse mixing in open channels remains incomplete (Fischer et al., 1979; Rutherford, 1994), especially for small and irregular streams. The simplest model for transverse mixing from a mid-channel source is the constant-coefficient model

$$L_z(\text{TR} = 1.1) = 0.093 * V_x b^2 / k_z \quad (1)$$

where L_z is the distance required to accomplish mixing to a tracer ratio of 1.1, V_x is the reach-average flow velocity, b is the reach-average breadth, and k_z is a transverse dispersion coefficient (Rutherford, 1994). This model assumes that turbulence is homogeneous along the stream reach, neglects complications near

banks, and uses reach-averaged measures of velocity and breadth which may be difficult to calculate (Rutherford, 1994) and which represent complicated channel morphologies poorly. More complex models (Fischer et al., 1979; Rutherford, 1994) taking into account longitudinal variation in the parameters of equation (1) are difficult to solve and even more difficult to parameterize. Perhaps the biggest problem is that all mixing models require values for k_z , and this parameter so far cannot be calculated from even the most detailed knowledge of channel characteristics (Lau & Krishnappan, 1981; Rutherford, 1994).

The lack of a fully predictive mixing model for small streams leaves us with two choices (aside from measuring mixing directly): we can measure reach-average k_z in the field, or we can extrapolate from a relationship between k_z and discharge based on values for rivers (Rutherford, 1994). Direct measurement of k_z , however, is no easier than measuring mixing; in fact, knowing over what distance to measure reach-average k_z requires advance knowledge of mixing distance itself! Extrapolation, unfortunately, is little better: available k_z estimates mostly pertain to medium to large rivers (there are none for natural channels with discharges $< 5 \text{ m}^3/\text{s}$), and available estimates can vary by an order of magnitude for any given discharge even among channels of broadly similar morphology (Rutherford, 1994, his Fig. 3.6).

If quantitative prediction of mixing lengths is not yet feasible, the situation is somewhat better for a qualitative understanding of how mixing is affected by major stream features. There is wide agreement (Lau & Krishnappan, 1981; Rutherford, 1994) that mixing should be accelerated by bends and channel constrictions (which tend to generate depth-structured transverse currents). In our streams this shows up as significantly faster mixing in complex channels compared to simpler ones, and across constrictions vs. simpler channels. Our faster mixing across pools also makes sense: flow entering a pool will form a decelerating jet, and the instability of such jets tends to generate transverse currents. In a small pool, these currents could produce rapid mixing (although in a larger pool, dead zones along pool margins might counterbalance the jet effect).

Recommendations for stream ecologists

Transverse mixing distances in small streams appear to be on scales that make mixing of potential import-

ance for our understanding of stream communities. We make three recommendations for stream ecologists.

Expect heterogeneity

Because mixing is not instantaneous, we should expect concentrations of transported materials in streams to show fine-scale heterogeneity whenever those materials enter the flow at restricted sources (or leave it at restricted sinks). It remains unknown how common such sources are for natural materials, but they are certainly common for pollutants and for experimentally added materials. The idea that streams will show spatial heterogeneity is far from new (Palmer et al., 1997); our contribution is to show that transverse heterogeneity can be expected in concentrations of transported material. Such heterogeneity has been downplayed (e.g. Hynes, 1970; Ciborowski & Craig, 1989; Allan, 1995; Fonseca & Hart, 1996). Such heterogeneity can exist in real streams: for instance, nitrate concentrations varied up to 10-fold across the 3 m breadth of an Arizona stream (Dent, 1999), and capture rates of chironomid exuviae varied 6-fold between nets 8 m apart in an Australian stream (Hardwick et al., 1995). Ecologists should integrate this form of heterogeneity into their conceptual models and experimental designs.

Exploit heterogeneity

Heterogeneity in transported materials may represent a valuable opportunity in two distinct ways. First, where stream organisms are nutrient-limited (e.g. Hart & Robinson, 1990, Wallace et al., 1997), local heterogeneity in dissolved nutrients or suspended organic particles offers itself as a variable for inclusion in explanatory models of stream community structure, alongside more familiar kinds of heterogeneity such as that in substrate (Tolkamp 1982, Benke et al. 1984) or current velocity (Hart & Merz, 1998). Second, clever manipulations of transported materials (for instance, additions of nutrients, particles, or predator odors; McIntosh et al., 1999) can exploit incomplete mixing to achieve side-by-side control and treatment experimental units. This approach offers a powerful paired design to control for variation among replicates along a stream reach or across multiple reaches or streams.

Measure mixing

It may be dangerous to make assumptions about mixing lengths without field measurements. For some experimental designs, mixing will not matter; but for

others (particularly those measuring effects of substances introduced to streams via point-source additions) good experimental design will often require at least rough estimates of mixing. Such estimates seem to be reported only rarely, even in experiments for which they are essential.

Estimating mixing need not require methods as time-consuming as ours. For many applications, what is necessary is the choice of a longitudinal distance over which mixing is either negligibly complete or negligibly incomplete, and this can often be determined (e.g. Hart & Robinson, 1990) with a small pilot study using chloride or visible dyes. With such estimates in hand, ecologists can be sure that mixing is neither too complete nor too incomplete for their experiments to work as designed.

Finally, ecologists should also directly measure heterogeneity in transported material (the complement of mixing) in natural streams. Almost nothing appears to be known about the magnitude or spatial structure of this heterogeneity, although a few studies have documented important heterogeneity over very small scales (Hardwick et al., 1995; Dent, 1999). Our results indicate that such heterogeneity, once established, may not always decay very quickly. Therefore, if restricted or near-point sources of transported material are common in streams, mixing will often be too important to ignore.

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