Peer-reviewed Research Article

A Method for Using Magnetic Tracer Stones to Monitor Changes in Stream Channel Dynamics

Brett Eaton (UBC), Marwan Hassan (UBC), and Jeff Phillips (Skagit River System Cooperative)

Geoscientists, hydrologists, foresters, and biologists who are interested in stream channel dynamics or fish habitat characteristics often need information on bedload sediment transport dynamics. Sediment transport is arguably the most important factor affecting the physical habitat of a riverine ecosystem and is fundamental to understanding morphologic changes occurring in stream channels. Unfortunately, it is exceedingly difficult to predict and equally difficult to measure directly in real time using sediment traps.

Magnetic tracer stones have been used in gravel bed rivers to estimate: the average distance of movement for sediment eroded by the river; the typical depth of the streambed subject to erosion and deposition (called the active layer); and the volume of sediment transported during a particular flood event (Hassan and Ergenzinger 2003). This information can be used to estimate the event-scale sediment transport rates, which are useful indices of the channel dynamics. This article summarizes research on the ways in which event-scale tracer stone displacements can be estimated from flow conditions and describes a methodology for directly measuring bedload movement of individual flood events.

Using what is known from detailed tracer studies, it is possible to employ a simplified tracer stone methodology in a more applied context, such as stream channel monitoring, without significantly affecting the quality and interpretability of the results. In the first part of this article, we describe the basic equations relating the behaviour of tracer stones that are initially placed on the bed surface and that are about the same size as the median surface grain size to the behaviour of the entire bed material population. Since sediment transport is a surface phenomenon, the step length for these particles is representative of the average step length for material that is transported during the flood (Church and Hassan 1992).

In the second part of the article, we describe the methods developed at the University of British Columbia (UBC) for constructing tracer particles that represent the median grain size, deploying them in the field, and ultimately recovering them after a flood event. The tracer methodology described here was originally developed for use at Fishtrap Creek. In that study (described in detail in Phillips 2007), the tracers were divided evenly into four heterogeneous groups of 100 particles each (labelled A, B, C, and D) and placed on the launch lines shown in Figure 1. Launch lines were chosen to document sediment mobility throughout the study reach. The tracers were placed on the streambed before the onset of the snowmelt

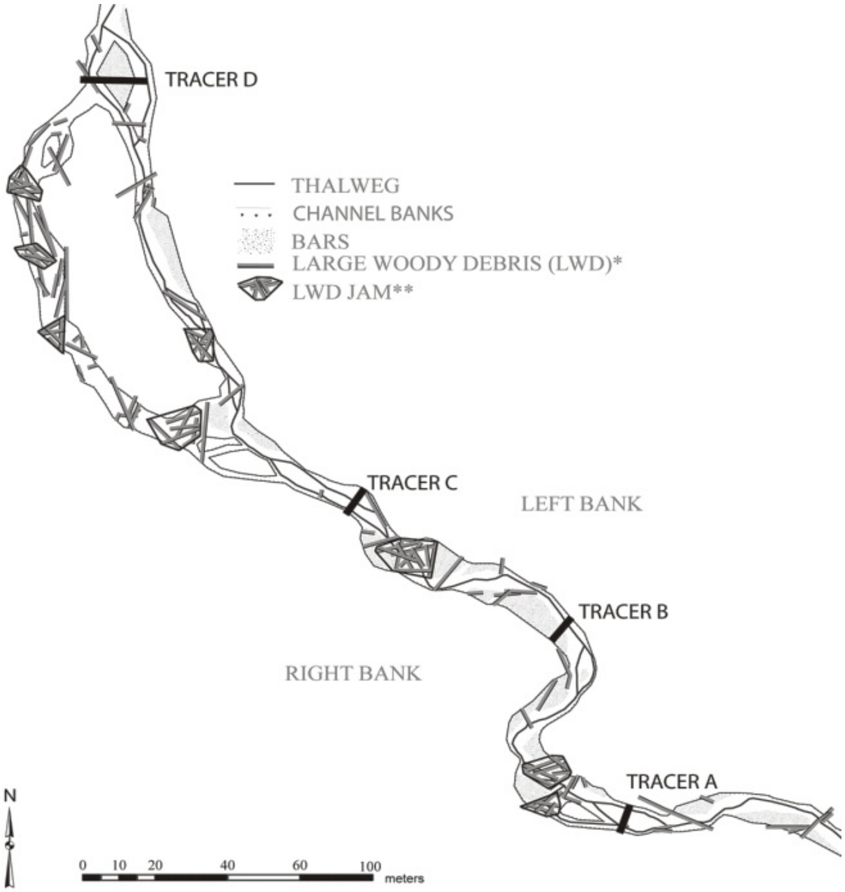

Figure 1. Planimetric map of the study area at Fishtrap Creek documenting the location of the four sediment tracer launch lines (A, B, C, D). In early April, 2006, tracers were launched in the upper, middle, and lower reaches of the study site: they were recovered in late July 2006.

Table 1. Estimated time required to complete a tracer study

Task	400 tracer stones at 4 launch lines (person-days)	100 tracer stones at 1 launch line (person-days)
Collect and drill stones	4	2
Label, seal, and paint tracers	3	1
Deploy tracers	2*	2*
Recover tracers	14*	8*
Analyze field data	2^+	2^+
Total	25 days	15 days

*Requires a field crew of at least two people. $^+$Analysis time depends on study objectives.

freshet and then recovered during low flows in August. The field crew was able to recapture about 80% of the stones launched from each line. Based on this project, we have summarized the time required to construct, deploy, and recover 400 tracers, deployed along four launch lines (Table 1). We have also estimated the time required for a tracer study using only 100 stones deployed at one launch line.

Estimating Event-scale Tracer Movements

This section summarizes the research that relates tracer movement to flow conditions. While the analyses (which are based on numerous datasets) reveal consistent, useful relations between flow conditions and event-scale tracer movement, there is significant scatter about these relations and high quality flow data are required to use the predictive relations. These relations are thus only useful in stream reaches where flow conditions are being continually monitored; even then, direct measurement of tracer displacements (as described in the following section) would be far more accurate.

One important result that significantly simplifies analysis is that the distance of travel for gravel particles is only weakly related to the particle size, making it possible to use the median surface size to characterize the behaviour of *all* of the bed material. Church and Hassan (1992) determined that, for unconstrained particles (i.e., stones already at the bed surface), there was a nonlinear relationship between grain size and mean travel distance, such that particles near the median surface grain size (i.e., the D_{50}) all moved similar distances. In contrast, particles much larger than D_{50} showed a rapid decrease in transport distances, with no movement typically occurring for stones larger than about five times D_{50}. As a result, Church and Hassan (1992) concluded that flow strength and duration have the most significant impact of travel distance, while particle size has only a second-order effect for most of the grain sizes commonly found on the bed. They present relations between the mean surface size and the mean distance of travel for all particle sizes. Other researchers have also documented that the mean travel distance decreases only slightly as a function of increasing grain size up to roughly the surface D_{50} and then declines rapidly for the coarse tail of the grain size distribution (Wilcock 1997; Ferguson and Wathen 1998). These observations make it reasonable to use tracers that are about the same size as the D_{50} to characterize the typical transport distances for the entire grain size distribution of the bed.

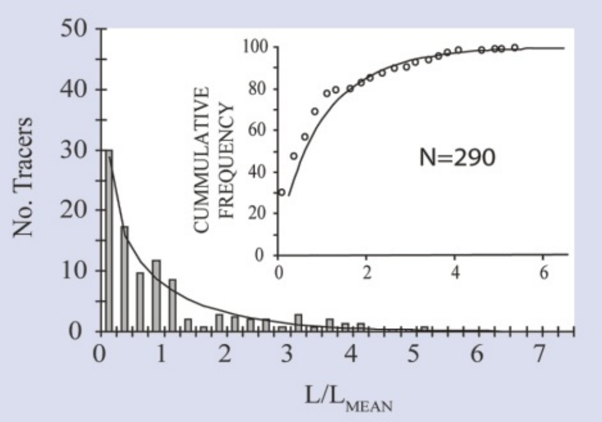

Figure 2. Typical tracer movement distribution for gravel bed rivers. In the main plot, the tracer densities for equally sized segments of stream channel are plotted against the distance of each segment from the start line divided by the mean travel distance. The raw data are shown as bars, and a fitted gamma distribution is shown as a line. In the inset figure, the cumulative frequency distribution is plotted against distance divided by the mean travel distance: the raw data are shown as open circles and the fitted gamma distribution is shown as a line. The data come from the tracer recovery at Fishtrap Creek in 2006.

The distribution of tracer travel distance is also remarkably consistent across a range of river systems, and appears to be well described by a gamma function (Hassan *et al.* 1991). A typical tracer distribution and fitted gamma function are shown in Figure 2. However, where morphologic constraints influence the travel distance distributions, various distribution types may result (Pyrce and Ashmore 2003). Pyrce and Ashmore also concluded that path length distributions are heavily influenced by characteristic pool-to-bar spacing in the stream such that, for peak flows that reach the bankfull stage, the mean transport distance should be equivalent to the pool-to-bar spacing.

Despite differences in the transport distribution shapes, typical bedload transport distances can be reasonably estimated using the average movements for all particle sizes. Hassan *et al.* (1992) assessed both the mean distance of movement for unconstrained surface particles (L_{MEAN}), as well as the virtual particle velocity (V_p), which is mean transport distance (L_{MEAN}) per unit of time for tracer studies in a range of different river systems. While the resulting equations are empirical, they appear to describe a common response for different flow regimes and environments. Both L_{MEAN} and V_p are reasonably well-related to the excess unit stream power, which is the difference between the unit stream power for the peak discharge and the unit stream power required to entrain the median grain size, D_{50}. Their results suggest that some characteristics of the bed material transport dynamics can be estimated, provided high-quality flow data are available.

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Unit stream power (in W/m^2) is estimated from the observed stream discharge (Q, in m^3/s), the average channel gradient (S, in m/m), and the average channel width (W, in m) using the following equation:

$$\frac{g\ \ QS}{W}$$

The term g is the acceleration of gravity (9.8 m/s^2) and is the density of water (1000 kg/m^3). The critical stream power, $_o$, (i.e., that required to entrain D_{50}) can be estimated using the following theoretically derived equation (after Ferguson 2005):

$$_{o}\qquad 2860\ \ D_{50}\quad^{1.5}\ \log\ \frac{12d}{D_{50}}$$

The variable d is the average flow depth at peak flow. All length units in the equation above are in metres. Hassan *et al.* (1992) relate both the mean travel distance and the virtual velocity for tracers moved during short, single peak flow events to the excess stream power for the peak discharge. Their equation for L_{MEAN} is:

$$L_{MEAN}\qquad 0.0283\qquad\qquad ^{1.44}$$

For short, flashy flood events, this equation can be used to estimate the mean step length even without deploying and recovering tracer particles, provided the streamflow has been accurately recorded. For longer snowmelt floods or multiple peaked events, it is more realistic to estimate the rate of tracer movement (V_p) as well as the duration of the transport event. Hassan *et al.* (1992) relate V_p to excess stream power according to the following relation:

$$V_p\qquad 0.00188\qquad\qquad _0\ ^{1.62}$$

In this equation, V_p is expressed in m/h. For transport events lasting several days, we recommend using daily average flows to estimate the transport distance associated with each day. Based on the equation for virtual velocity, the daily transport distance (L_{DAILY}) is approximately:

$$L_{DAILY}\qquad 0.045\qquad\qquad _0\ ^{1.62}$$

For example, Phillips (2007) estimated the mean step length at Fishtrap Creek in 2006 at about 100 m. The peak instantaneous flow for Fishtrap Creek reported by the Water Survey of Canada (WSC) was 8.8 m^3/s: using this value in Hassan *et al.*'s (1992) equation for L_{MEAN} predicts a travel distance of only 12 m, which is clearly inconsistent with the field observations. Based on the WSC's reported daily flows for 2006, and assuming a median surface grain size of about 55 mm, the critical stream power ($_o$) was exceeded for 22 days. The total predicted transport distance for these 22 days is 112 m. However, if we assume a median surface grain size of 50 mm, the equations predict a total transport distance of 198 m, indicating that this approach is highly sensitive to the selected input variables.

The sensitivity of the stream power based equations to the selected grain size is a major drawback, and is the primary reason that we advocate directly measuring transport distances using tracer stones. When continuous, high quality flow records are not available for the study stream, it is essential to use tracer stones for estimating the bedload transport dynamics. Using tracer stones obviates the necessity for collecting any kind of stream flow data to estimate the event-scale sediment transport rate.

Measuring Event-scale Tracer Movements

Constructing the tracers

The first step is to identify the size and number of tracers that you wish to deploy. We recommend using three size classes that bracket the median surface grain size distribution in that part of the channel where sediment transport occurs most frequently, since this is most likely to reflect the bedload grain size distribution. To determine the surface grain size distribution, locate a sample site that has a surface texture similar to that found in the main channel. Ideally, the sample site will be a dry, exposed part of the channel, but it is possible to sample sediment in shallow, slow-moving water. The best sample locations are typically found at the head of a channel bar or adjacent to a riffle. Then, establish a regular grid over the sample site: typically, the nodes of the grid should be spaced apart by no less than twice the diameter of the largest stone in the sample area. Collect the surface stones found at each node and record their particle diameter. The grid should be large enough so that at least 100 stones can be collected. The representative particle diameter is measured along the intermediate axis (i.e., the *b* axis; Figure 3), which represents the largest particle dimension measured perpendicular to the longest axis of the stone (the *a* axis).

As you are collecting and measuring the *b* axis diameters, classify each measured stone diameter into size classes based on the Wentworth size system. The boundaries for the size classes are 5.6, 8, 11, 16, 22, 32, 45, 64, 91, 128, 181, 256, and 363 mm. The easiest (and most accurate) way to estimate the size class for a particle is to use a template in which squares with the appropriate diameters have been cut: for example, if a particle passes through a square with a 45 by 45 mm opening but not through a 32 by 32 mm opening, it falls in the 32 to 45 mm size class. Once the data have been collected, identify the size class that contains the median grain size, D_{50} (i.e., the size for which half of the stones sampled are smaller and half are larger). This is done most easily (and accurately) by plotting the proportion of the distribution finer than a given grain size against grain size (Figure 4).

Once the median size class has been identified, collect a number of stones from the study steam that fall in the median size class, as well as in the size classes above and below the median. We recommend using three size classes to confirm the expectation that L_{MEAN} is relatively insensitive to particle size for the grains close to the D_{50}, and to account for any variations in surface particle size along the reach: using three size classes also gives some indication of the variability in the step lengths. For an accurate estimate of the average transport distance, 25–35 stones should be collected for each size class[1] for each launch line, corre-

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[1] We specify 25–35 stones per size class per launch line since, for normally distributed populations, the estimates of the mean and standard deviation are generally constant for n > 20.

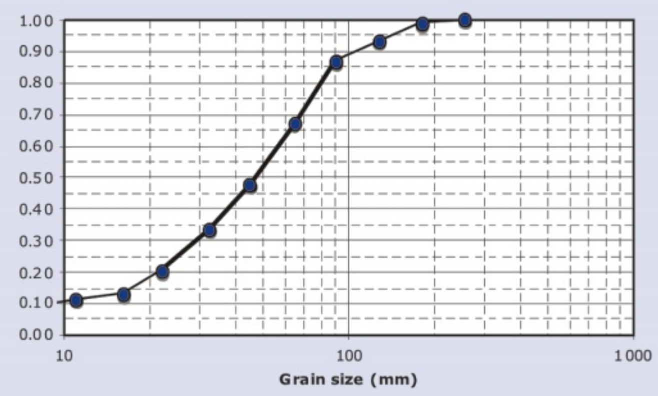

Figure 4. Grain size distribution from a bed surface sample from Fishtrap Creek.

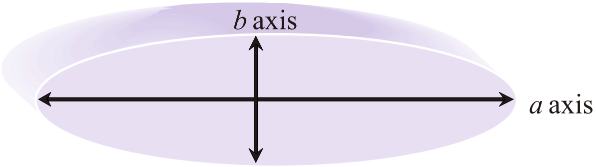

Figure 3. Definition of the a and b axes for a sediment particle.

sponding to about 90 stones per launch line. At least three launch lines should be used to identify any strong spatial gradients in the sediment transport patterns within a study reach: launch lines should be located just downstream of changes in channel morphology or at regular intervals along the channel where the morphology remains relatively constant (a spacing of about 5–10 channel widths is probably appropriate for most sites). For example, if we assume that four launch lines are to be used, and that the estimated D_{50} falls between 45 and 64 mm, it would be necessary to collect about 120 stones in each of the 45–64, 32–45, and 64–91 mm size classes.

In the laboratory or workshop, carefully clean each tracer stone, removing any algal growth or veneer of fine sediment that may be present. Then, using a thin wall diamond drill bit (Figure 5A), drill a hole about ½″–1″ deep into the stone. The tracer magnets will be placed in the hole, then sealed in place using clear epoxy. The drill will cut a circular slot into the rock, and a rock chisel should be used to remove the central core. The resulting hole must be large enough to accommodate the tracer magnets. The drill bit shown in Figure 5A has a 9/16″ diameter with a 5/16″ shaft, purchased for about $50 from Pothier Enterprises Ltd., Delta, BC. Between 20 and 100 stones can be drilled with a single bit, depending on the lithology of the tracers. When drilling the hole, the stone must be securely clamped in place, and the drill bit must be lubricated with water to prevent it from overheating. This can be accomplished by using a drill press designed to supply water directly to the head of the drill bit (Figure 5B), or by immersing the stone and clamping system in a tub of water. While a drill press is more convenient, a powerful handheld drill can be used to make the hole.

Once the hole has been drilled, the stone should be painted a bright colour to aid in identifying the stone. The stones pictured in Figure 5C were painted bright blue and yellow using fish-friendly aquarium paint. When establishing multiple launch lines, paint the stones for each line a different colour. Take care to completely cover the exterior of the rock, but avoid getting paint in the hole. Once the paint has completely dried, place two magnets in the hole. Ceramic magnets are suitable, and emit a strong signal that is easily detectable. The magnets that are typically used at UBC are disc-shaped with a diameter of 1/2″ and a thickness of 3/16″ and cost about $0.25 each (supplied by Tormag Industries, North Vancouver, BC). Then, place a paper label with a unique alphanumeric code on the top magnet, and seal the magnets and labels in place using clear epoxy. Print the label on write-in-the-rain paper using a laser printer, then cut to size so that the label fits into the hole. First glue the label onto one of the magnets and then place the magnet in the stone before adding the remaining epoxy. There should be at least 5 mm of epoxy above the surface of the label, and the epoxy should not protrude above the edge of the hole: the epoxy is prone to chip during transport, and if the label is too close to the surface, it can be exposed and ruined.

Deploying and Recovering the Tracer Stones

As the field crew places the tracers in the stream at a launch line, they should carefully record the identification label number of each stone. The tracers from all three size classes should be evenly distributed along a launch line that is perpendicular to the flow, extending between the high water marks on the left and right banks (Figure 5D). In snowmelt-dominated systems where the timing of the peak flow is relatively predictable, it is often possible to launch the tracers a few weeks before the annual peak flow, thereby minimizing the likelihood that the tracers will be tampered with. In systems where access in the early spring is problematic (due, for example, to road conditions and/or snow and ice cover), it is probably advisable to place the tracers in the stream in the late fall. The tracers should be placed on the bed surface, and then firmly pressed into the bed with the heal of a boot: the idea is to wedge the stone into the surface to about the same degree as would be typical for a natural stone on the bed.

The recovery of the tracer stones is the most labour-intensive part of the job, and should ideally be conducted during summer low flows. Starting at the upstream-most launch line, a fibreglass tape is stretched down the centreline of the channel and secured in place. Then, a magnetic locator is used to carefully search the entire streambed, progressing systematically in a downstream direction. A magnetic locator detects both the background magnetic fields associated with the rocks in the stream, as well as the signal emitted by the tracer magnets and other metallic items in the streambed. The

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magnetic locator used by researchers at UBC is the Schonstedt Magnetic Locator (model GA-52Cx): these units are commonly available from most survey equipment dealers. The locator comprises a long metal sensor (called the "wand"), which can be immersed in water, and a housing for the circuitry that must never be immersed in water. The locator emits an audible signal, the pitch of which is proportional to the strength of the local magnetic field near the tip of the wand. On the upper housing, there is a control for the sensitivity and for the volume level. Typically, a sensitivity setting in the middle of the range provides the best compromise between "false" signals from naturally magnetic rocks and the ability to detect tracer stones at depth. For a more precise fix on the tracer location, reduce the sensitivity.

Before beginning the tracer recovery, dig several holes in the streambed with depths ranging from 5 to 70 cm, bury a tracer stone in each hole, and then use the locator to search the general area surrounding each hole on various sensitivity settings. This will give the operator a general sense for the background signals, the characteristics of tracer signals, and the detection limits for the instrument. False positives — when the field crew dig for a tracer where there is none to be found — are unavoidable, and a low percentage (e.g., 5–10%) of false positives (as opposed to none at all) is a good indication that the searching procedures are rigorous enough to obtain adequate tracer recovery rates. The field crew should also carefully read the instruction manual for their magnetic locator, which typically describes the measurement principle, provides guidelines for use of the instrument, and illustrates the nature of signals produced by various target with a range of magnetic orientations.

In the Fishtrap Creek watershed, which has a mixture of ferromagnetic lithologies that can produce relatively strong false positive signals, the field crews could reliably detect magnetic tracers buried by up to 50 cm of sediment, even when working in water as deep as 1 m (provided the current is relatively slow). This, however, takes time and the field crew often had to dig for up to an hour to find a deeply buried stone in a pool. To recover a representative sample, it is generally necessary to pursue a potential signal until the tracer is found or until it can be confirmed as a false positive. Tracers buried deeper than 50 cm were also detectable in Fishtrap Creek, but the orientation of stone (and thence the magnetic field) had to be favourable, and we infer that tracers buried deeper than 50 cm were not well represented in the population of recovered tracers. The distributions of burial depths (normalized by the median surface grain size) for Fishtrap Creek and two other streams in British Columbia are presented in Figure 6. While the distributions vary, it is clear from those examples that stones are rarely found buried deeper than 10 times the D_{50}, which is probably a useful guideline for estimating the maximum potential burial depth in a stream where the tracers will be placed. At Fishtrap Creek, a crew of two workers (one searching for stones, the other digging for them) was able to recover between 20 and 50 stones in a single day, depending on the density of tracers in the area and the depth of burial.

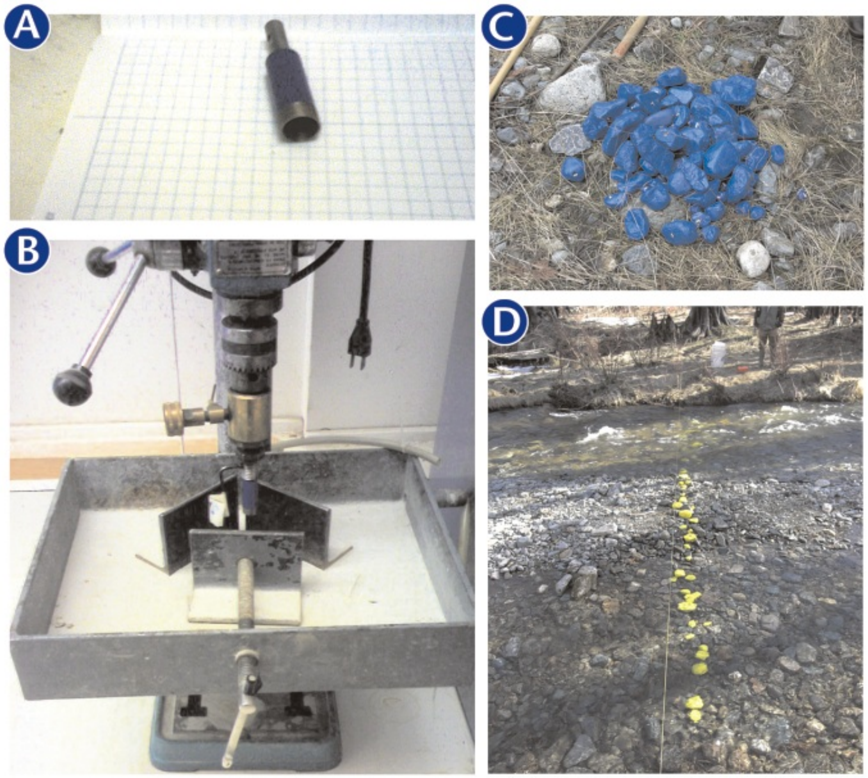

Figure 5. A) The drill bit used to drill a hole in the tracer particles. B) The drill press and clamping system used at UBC. C) A collection of tracer stones to be deployed at Fishtrap Creek. D) The tracers deployed in the field at the launch line.

Once a stone has been recovered, the field crew should write down the label number and colour of the tracer (particularly if the label is difficult to read), and measure the *b* axis dimension. Then, they should measure the tracer's position and burial depth. The position of a recovered tracer stone is defined using two measurements: the longitudinal distance along the channel centreline from the initial launch line (X'); and the lateral distance across the channel from the channel centreline (Y'), measured at right angles to the centreline. Note that tracers that are left of the centreline (looking downstream) have negative Y' values while tracers to the right of the centreline have positive Y' values. The burial depth (H') should also be recorded. Burial depth is measured from the

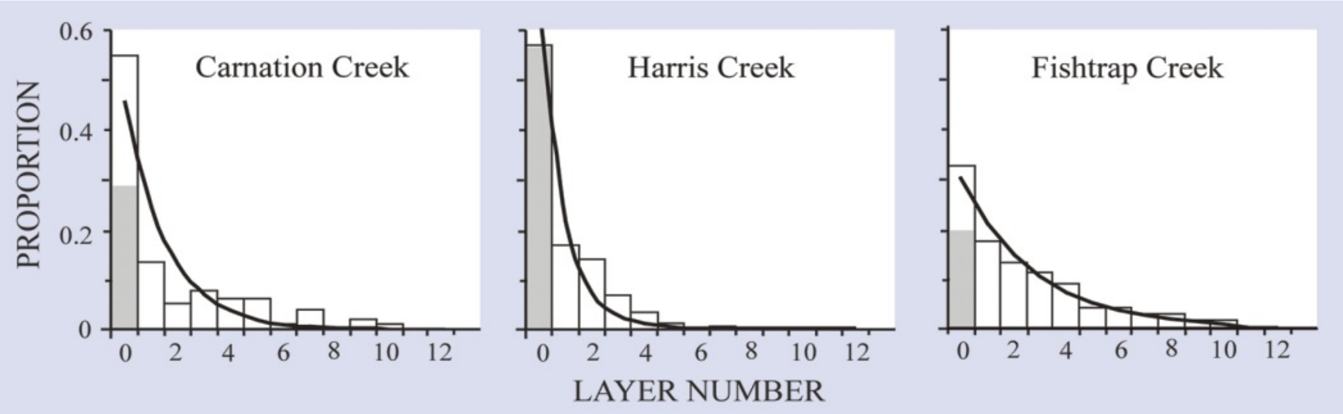

Figure 6. Particle burial depths for flood events in three different streams in British Columbia. The proportion of the tracers found in each layer is plotted against the layer number (layer 0 is at the surface, layer 1 is just below that, layer 2 is below that, etc.). A layer is defined to be as thick as the median surface grain size (i.e., the D_{50}).

base of the tracer to the bed surface. Since it is difficult to determine the exact height of the bed surface, it is advisable to establish a reference plane spanning the hole in the direction of flow (e.g., the handle of a shovel laid down upon the bed surface), and then to measure the burial depth relative to the reference plane. Where applicable, the depositional morphology should also be recorded (e.g., pool, riffle, glide, bar, bar edge, thalweg, or LWD step). Hassan *et al.* (2005) provide a good summary of morphologic terminology that is appropriate for mountain streams such as those common in British Columbia. Once recovered, a tracer should be stored in a container well away from the search area (so as not to interfere with the search); the hole should be refilled, but only after it has been carefully searched to ensure that no other tracers are in the hole.

> *While tracers can provide a great deal of data on how a system is behaving, the interpretation of that data requires a broader scientific perspective on the land use history and geomorphic setting in which the tracer study was conducted.*

To recover a representative proportion of the tracers, it may be necessary to search well downstream of the study reach. At Fishtrap Creek, tracers moved as far as 500 m downstream of the study reach. Typically, the search was abandoned only after the crew failed to find any tracers in a 100-m section of stream channel.

Interpreting the Results

The goals of the monitoring or research program will dictate the analyses that are required. Hassan and Ergenzinger (2003) discuss in some detail the various questions that can be answered using tracer data, and the limitations of this approach; they also provide an overview of the analysis that is commonly conducted in research. One example of the potential uses of tracer data is presented by Phillips (2007), who analyzes tracer data to estimate the event-scale sediment transport rate for a stream. Some of the most important insights are qualitative ones gained during the recovery. The typical areas where tracers are found give insight into the channel dynamics and the overall level of activity for the various parts of the channel. Therefore, the recovery team should include at least one appropriately trained geoscientist or engineer who can make the necessary qualitative observations and document them appropriately.

Generally, the distribution of transport distances is analyzed by normalizing the distance of movement (L) by the arithmetic mean travel distance (L_{MEAN}). The normalized travel distances often follow a gamma distribution. It will be informative to compare the transport distributions for the tracers grouped by launch line, and distributions grouped by particle size. Phillips (2007) showed that the residuals associated with a fitted gamma function were well correlated with the general patterns of morphologic change in a reach, where stable transport reaches were associated with observed tracer densities less than predicted by the gamma function and aggrading bars associated with tracer densities greater than predicted (Figure 2).

In addition to providing information on the travel distance, tracers offer information on the characteristic burial depths for the transported sediment. The observed burial depths have been used to indicate scour and fill depth, to estimate the volume of available sediment, and to determine the degree of vertical mixing (Hassan and Church 1994). When analyzing burial depths, it is common to normalize the depth by the median surface size (i.e., the D_{50}): the active layer thickness scales with grain size of the bed, not the size of the width or depth of the channel, so data from different rivers are directly comparable when normalized by the surface grain size. While the depth of the active layer varies from place to place and from event to event, burial depths are almost always exponentially distributed, as shown for three examples in BC streams (Figure 6).

Whatever the intended analysis, it is important to consider the degree to which the data are representative of the typical system dynamics. The investigator should consider whether (1) the magnitude of the peak flow was unusually high/low; (2) the duration of the peak flow was abnormally

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long/short; and (3) the tracer recovery rate was sufficiently high. Finally, while tracers can provide a great deal of data on how a system is behaving, the interpretation of that data requires a broader scientific perspective on the land use history and geomorphic setting in which the tracer study was conducted. ~

For more information, contact:

Brett Eaton
University of British Columbia
Tel: (604) 822-2257
Email: brett.eaton@ubc.ca

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