The Rolling Stones of Soda Butte Creek

Tracing the Movement of Individual Gravel Particles Yields Insight on Sediment Transport and Channel Change in a Dynamic Gravel-Bed River

Dr. Carl J. Legleiter & Devin Lea

For the rivers of northern Yellowstone, the only constant is change. Visitors to the park's northeastern corner often gaze across the Lamar River and its principal tributary, Soda Butte Creek, in search of wolves or grizzly bears. Many wildlife enthusiasts return year-after-year; and the more astute among them also might notice, between sightings, that significant changes occur in the streams that flow beneath Jasper Ridge and Mount Norris. This portion of Yellowstone is comprised of readily erodible Eocene volcanic rocks, recently uplifted and carved by glaciers that left behind steep valley walls. The combination of weak rock, high relief, and a propensity for large floods makes the rivers draining this landscape highly dynamic (Meyer 2001), with many reaches experiencing dramatic changes on nearly an annual basis. This perpetual reworking of channel beds, floodplains, and adjacent riparian communities creates an intricate mosaic of terrestrial and aquatic habitats. In this environment, geomorphic complexity fosters biological diversity and provides crucial refugia for some of the park's most important species, including native cutthroat trout. It's also a great spot to watch some rocks roll.

Rivers, Rocks, & Landscapes

Fluvial geomorphology, the scientific discipline concerned with rivers and related landforms, is based upon a fundamental premise: a close coupling exists between the processes of flow and sediment transport that act to shape channels and the size, shape, and spatial arrangement of morphologic elements such as bars, pools, riffles, and bends. In turn, these features exert a direct influence on the processes responsible for their formation and maintenance. In other words, alluvial rivers (those with beds and banks of mobile sediment) are self-formed, the authors of their own geometry. Complex interactions between form and behavior thus dictate how, and how rapidly, a channel's morphology will evolve over time. This evolution might occur in a gradual, relatively predictable manner, as observed along a gently meandering stream like Slough Creek (another tributary to the Lamar), or in more stochastic fits and spurts, as observed along Soda Butte Creek (Legleiter 2014).

This intimate connection between the movement of sediment and the form of a channel also serves as the foundation for an increasingly popular, inverse method of estimating sediment transport rates. The so-called morphologic approach involves inferring patterns and rates of bed material transfer and storage from observations of channel change, which can be obtained via repeat topographic surveys and/or remote sensing. An important advantage of this technique–as opposed to directly measuring moving bedload–is morphologic methods yield an integrated summary of the geomorphic consequences of the transport process (Ashmore and Church 1998). Although volumes of erosion and deposition can be determined by differencing digital elevation models from two distinct "before and after" time periods, determining transport rates requires additional information on the speed at which this sediment is routed through the fluvial system. Such data can be obtained by tracking the movement of individual sediment particles. These "tracer studies" provide a means of assessing the mobility of various grain sizes, determining travel distances, and identifying preferred locations for sediment to come to rest.

Bars form where many individual sediment grains accumulate in a single location, a preferred rest stop for particles to pause and congregate before continuing on. The hypothesis, tested by Pyrce and Ashmore (2003, 2005) in the controlled setting of a laboratory flume, is that bar spacing is roughly equivalent to the distance traveled by most gravel particles during large, channel-forming flows. Some rocks will move farther, some not so far, and others not at all (particularly during dry years); but the majority will travel about 5-7 times the channel width, which also happens to be the average distance between point bars in a meandering stream.

Although Pyrce and Ashmore (2003, 2005) examined path length distributions in a flume, the relationship between travel distance and channel morphology is not as well-established in natural rivers. We highlight results from a long-term tracer study that involved recording a few rolling stones as they made their way down Soda Butte Creek between 2006 and 2011. More specifically, our work was motivated by the following research question: How far along the river do individual sediment grains tend to travel each year, and does this distance reflect the spatial structure of the channel's morphology (i.e., the spacing between bars)? We also compared particle path lengths from three stream reaches with different morphologies and geomorphic histories, and investigated how these distributions were influenced by hydrologic conditions, as indexed by peak flow magnitude during spring snowmelt.

Morphodynamics of Northern Yellowstone's Gravel-bed Rivers

We initiated tracer studies on three reaches of Soda Butte Creek in the summer of 2006: Footbridge, Round Prairie, and Hollywood (figure 1). We randomly sampled gravel particles from the streambed along a series of transects and hauled the rocks back to our field station for tracer installation. Briefly, this process involved: 1) measuring the size and density of each particle; 2) excavating a cylindrical hole in the rock with a hammer drill (figure 2a); and 3) inserting a passive integrated transponder (PIT) tag (figure 2b) and resealing with epoxy.

PIT tags are a type of radio frequency identification technology widely used to track wildlife, including fish, and more recently to trace sediment movement (e.g., Lamarre et al. 2005, Liébault et al. 2012). The pill-shaped tags are passive in that they do not contain a battery but rather are activated when exposed to an electromagnetic field emitted by an antenna. Each tag broadcasts a unique code read by a mobile antenna (figure 2c), allowing individual particles to be identified and relocated without having to excavate the tracer grain from the bed. The most important advantage of PIT tags is that by recording where individual tracers were initially placed and subsequently found, one can learn about bed mobility, particle movement, and depositional setting.

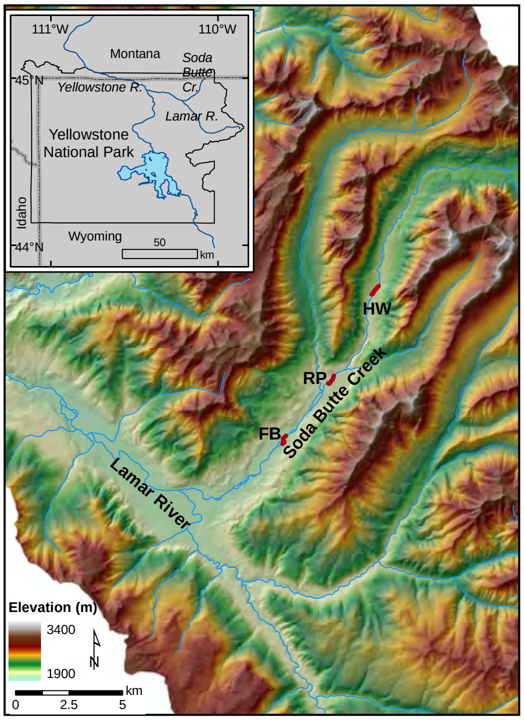

Figure 1. Location map of tracer study performed along three distinct reaches of Soda Butte Creek in the park's northeastern corner. These sites include: Hollywood (HW), Round Prairie (RP), and Footbridge (FB). Adapted from Legleiter (2014).

Figure 2a.

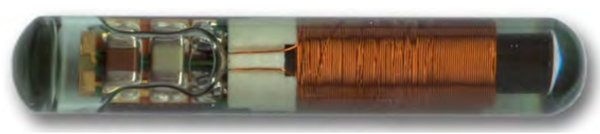

Figure 2b.

Figure 2c.

Figure 2. The tracer study involved (a) using a hammer drill to excavate a hole in each particle, (b) inserting a Passive Integrated Transponder (PIT) tag with a unique radio frequency identification code, and (c) searching for the tagged particles with a mobile antenna.

In this study, the tagged particles were returned to the same cross-sections from which they were obtained and their locations recorded with a GPS. The tracers were carefully inserted into the bed in as natural an arrangement as possible, by replacing a similarly sized particle with one of the tagged gravels. Tracer installation was completed in August and September along with detailed surveys of each study reach. These topographic data defined the morphologic context of the initial tracer locations and also provided digital elevation models for calculating erosion and deposition after the sites were resurveyed (Legleiter 2014).

Tracer recovery involved sweeping channels and bars with a hoop-shaped mobile antenna, performed by the most patient member of our research team (the lead author's father) in a systematic, cross-section-based pattern to avoid gaps in coverage. The search area extended several channel widths beyond where tracers were seeded and increased in size each year as the tracers made their way downstream. When a PIT tag entered the antenna's field of view, we were notified by an audible siren. A handheld computer attached to the antenna displayed the tag's code, which we recorded along with the GPS coordinates of the tracer's new location. The shortest distance between two points is a straight line; but rivers are curved, so travel distances were measured along the channel centerline using the algorithm developed by Legleiter and Kyriakidis (2006).

Tracer recoveries were limited to 2007 and 2008 for the Round Prairie and Hollywood sites but continued annually through 2011 for the Footbridge Reach. Each year we revisited the last known location of each tracer to determine whether or not the particle had moved, even if we were not able to recover the particle in a new location. By recording the life histories of these rolling stones, we were able to analyze their mobility, travel paths, and depositional fate.

Where Rocks Roll

One challenge of field-based river research, and a reason why flumes provide an appealing alternative, is that the observations one makes depends on a number of variables over which one has no control. Foremost among these factors is the weather, specifically the magnitude of each year's spring flood. Hydrologic conditions for 2006-2011 are summarized in figure 3, which plots streamflow as a function of time for two USGS gaging stations. The gage on Soda Butte Creek located near our Footbridge site was discontinued at the end of the 2008 water year, so we also included data from a gage on the Lamar River farther downstream near Tower. Figure 3b provides an indication of regional hydrologic conditions during the final three years of our study, after the Soda Butte gage was deactivated. In snowmelt-dominated watersheds, sediment movement occurs mainly during spring runoff, with the transport rate depending strongly on the magnitude and duration of high flows. As context for the streamflows observed during our study, the dashed horizontal lines in figure 3 represent the median of the annual peak discharges recorded over the entire period of record for each gage. The median annual flood serves as an estimate of the kinds of large, but not unusual, flows that occur frequently enough to shape a channel. Although varying hydrologic conditions were a complicating factor, this variability created an opportunity to compare particle mobility, path length distributions, and depositional settings between very dry (2007), typical (2008), and relatively high (2010) runoff years.

In essence, the goal of a sediment tracer study is to monitor the movement of individual particles by recording their location each time they are recovered. A sequence of maps depicting the spatial distribution of tracers during each year provides a convenient visual display of how the marked grains traveled downstream and where they paused en route. Tracer maps for the Footbridge site are presented in figure 4 to illustrate this technique. To provide morphologic context for tracer loca-

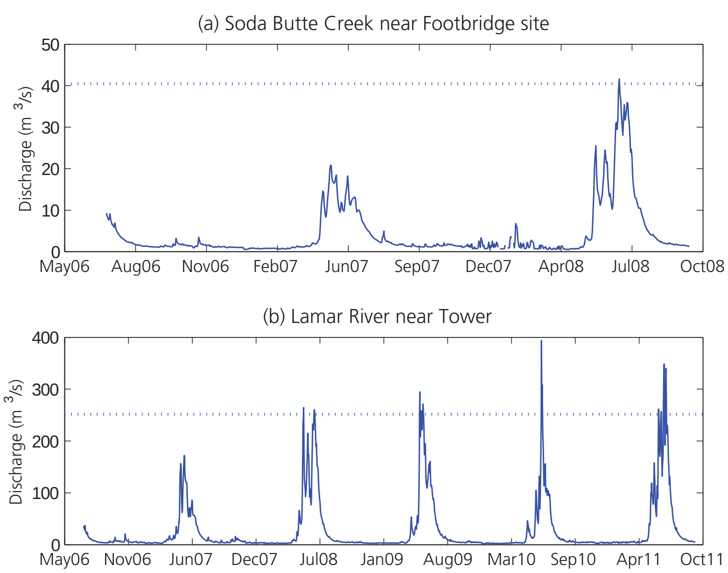

Figure 3. Hydrographs summarizing streamflows during the tracer study for (a) a gage located on Soda Butte Creek near our Footbridge site that was deactivated in 2008 and (b) a gage farther downstream along the Lamar River that is not directly comparable to the Soda Butte site but provides an index of regional hydrologic conditions during the latter portion of the study. The dashed horizontal lines represent the median annual peak discharge for each gaging station over the entire period of record.

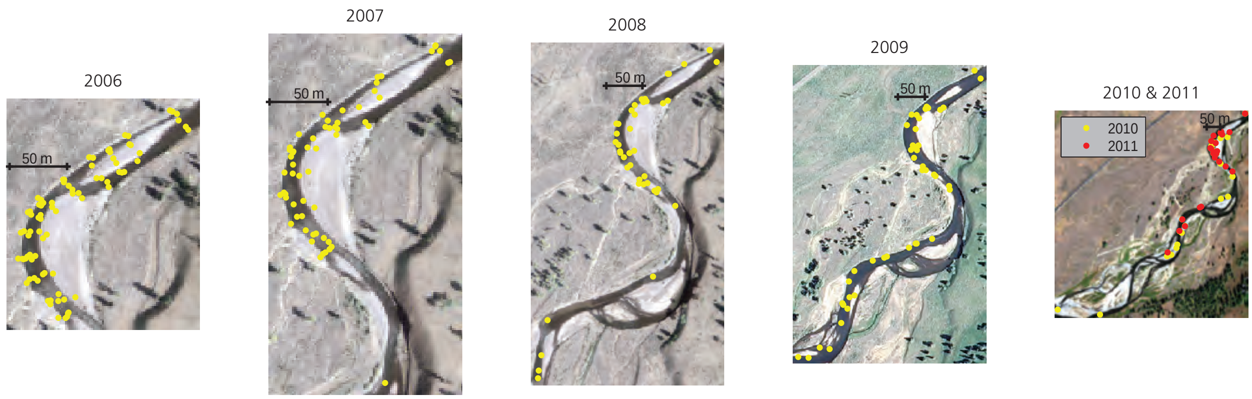

Figure 4. Tracer maps for the Footbridge study site. In the first panel, a 2006 image is used as a backdrop to display the initial placement of the tracers. The second and third panels use the same image as a backdrop but depict the locations of recovered tracers in 2007 and 2008. The fourth panel uses a 2009 image to provide morphologic context for the locations of tracers recovered in 2009. The final panel uses an image from 2011 to show tracer recovery locations for 2010 and 2011. The scale bar represents the same distance in all five maps and is anchored in the same location to provide a consistent spatial reference as we zoom out from the 2006 to the 2009 image and then again to the 2011 image to reflect the dispersion of tracers over a greater distance along Soda Butte Creek.

tions and summarize channel changes that occurred, we used a time series of images as background for these maps. As the tracers traveled farther downstream and dispersed over time, displaying all of their locations required larger image extents; so we zoomed out from one map to the next while retaining a common scale bar anchored in the same location to serve as a consistent reference throughout the time series.

For both the Hollywood and Round Prairie study sites, the infilling of channels that had been active when we initially placed our tracers buried many of them. As a result, we discontinued recovery efforts at these two sites after the 2008 field season. At the Footbridge reach, channel changes were more gradual and the search carried on for three more years through 2011 (figure 4). The first panel of figure 4 shows the initial placement of 83 tracers on a series of cross-sections distributed along the sweeping meander bend to the left (looking downstream, flow is from top to bottom of the image). Using the same 2006 image as a backdrop, the 2007 map shows some of the tracers strayed slightly from the original transects but many remained in place. The most salient feature of this map, and the sole reason for the different scale and extent than the 2006 map, is the single tracer recovered 142 m from its starting point, a full meander wavelength downstream where the channel begins to curve back to the right. This surprising stone indicated that even during low flows when most rocks move little, if at all, the occasional outlier can still sprint several channel widths downstream. Consistent with our observations from the other two sites, this particle came to rest on the lower margin of a point bar, implying gradual downstream translation of the bar.

By 2008, after a more typical spring flood, only 35 of the original 83 tracers were relocated at the Footbridge site; and 11 of those remained in the same locations as in 2007. For the 24 particles that were mobilized, preferred depositional environments included the upstream shoulder of the large point bar on the left bank of the bend in the upper half of the 2008 map, the small but growing bar on the right bank where the channel curves left in the middle of the map, and in shallow water toward the bottom of the image. In 2009, recovered tracers were distributed fairly evenly over an expanded length of Soda Butte Creek, with a dozen particles having traveled a full meander wavelength down the river. Sites of focused deposition were less evident in the 2009 map, perhaps due to the larger runoff during that year, which not only would have entrained more grains but allowed them to remain in motion through areas where they might have been deposited had the discharge been lower. A longer duration of higher flow also might have enabled some tracers to take more than one "hop" during the runoff.

The largest streamflows occurred in 2010 and corresponded to the greatest path lengths we observed at the Footbridge site, including a record leap of 779 m! This grain finally came to rest on a large bar on the right side of the channel, a full three meander wavelengths downstream from its initial 2006 location. The most popular rest stop in 2010 was near the water's edge on a point bar on the left side of the channel, shown in the middle of the final map in figure 4. This map also includes tracer locations for 2011, when recovery dropped to 18 particles. By this time, we were able to relocate many of the tracers that remained near their previous locations, to which we could navigate using GPS; but the particles that had moved the greatest distances could no longer be found. As time went on and some tracers traveled farther downstream while others remained in place, we were forced to expand our search over a larger area. The increased time and effort required to search this growing domain, coupled with diminishing returns in terms of number of tracers recovered, caused us to end the study after 2011. Even if we're no longer looking for them, the rocks are still out there, rolling along.

A Summary of Particle Path Lengths

Table 1 summarizes tracer recovery, mobility, and travel distances for each reach. Although our recovery efforts provided detailed information on the specific trajectories of each individual grain, we required a more concise summary, aggregated over the population of particles, to gain insight as to typical travel distances, differences among reaches, and hydrologic controls on sediment transport. In figure 5, cumulative distribution functions (CDFs) are used to describe annual travel distances. The vertical axes of these plots indicate the proportion of recovered tracers that traveled a distance less than or equal to the distances on the horizontal axis. Represented in this manner, immobile particles occur in the lower left corner, the rocks rolling the farthest plot at the upper right, and the shape of the line in between depends on the distribution of path lengths for the other tracers. A steep segment of the CDF implies many particles had similar path lengths, resulting in a tight, highly peaked distribution. Conversely, the CDF would rise gradually if the particles were distributed more evenly over a broader range of path lengths. In comparing two CDFs, the distribution with a larger number of longer travel distances would plot farther to the right.

Table 1. Summary of tracer recovery, mobility, and travel distances for each reach. The number of tracers initially placed in 2006 is given in parentheses after the reach name.

	Number recovered	Number of mobile tracers	Median travel distance (m)	Maximum travel distance (m)
Hollywood (77)				
2007	61	48	15.4	257.7
2008	17	16	114	481.3
Round Prairie (74)				
2007	65	46	6.1	187.7
2008	48	31	25.8	234.9
Footbridge (83)				
2007	59	43	6	142.3
2008	35	24	19.9	426.9
2009	35	10	307.1	691.7
2010	26	12	27.9	778.6
2011	18	16	123.7	515.8

For Hollywood, the low flows in 2007 resulted in a large number of immobile or barely mobile particles, with over 50% of the tracers moving less than 10 m (figure 5a). Following the greater runoff in 2008, the CDF shifts noticeably to the right, with only one immobile particle recovered and about half of the tracers moving more than 100 m. The pronounced differences between the 2007 and 2008 path length distributions for Hollywood were at least partially due to the extensive channel changes during this time—incision of a new channel and infilling of the old channel, which buried many of the tagged particles beyond the read range of our antenna system. Nevertheless, our observations—greater path lengths in the year with higher runoff and a path length distribution peaking at a distance of seven channel widths, approximately equal to the spacing between bars—were consistent with the hypothesis that the spatial structure of river morphology reflects the distance traveled by individual sediment particles during channel-forming flow events.

Results from Round Prairie were similar in many respects (figure 5b). In this reach, which is primarily depositional in nature, nearly 70% of the tracers relocated in 2007 were immobile or moved less than 10 m. As in Hollywood, higher flows in the spring of 2008 transported more of our tracers over greater distances, with fewer immobile particles, suggesting flows of sufficient magnitude are needed to transport sediment over significant distances. The connection to channel form is less clear in Round Prairie due to the braided morphology of this reach; bars are arranged irregularly and tend to be more closely spaced.

The Footbridge reach was the most stable site during our investigation, which allowed us to continue tracer recoveries through 2011. Again, the CDF graph indicates that little sediment movement occurred during 2007 (figure 5c). In 2008, recovery dropped to 35 tracers (24 were mobile); but the particles we relocated tended to move farther, as indicated by the CDF's shift to the right. The path length distribution was also less skewed in 2008 than 2007. In 2009, the same number of tracers was recovered, but only 10 were mobile. Based on this small sample size, the path length distribution appeared far more symmetric with relatively few particles moving short distances. The peak flow recorded in 2009 for the Lamar gage exceeded the median annual flood for this station; and the increased

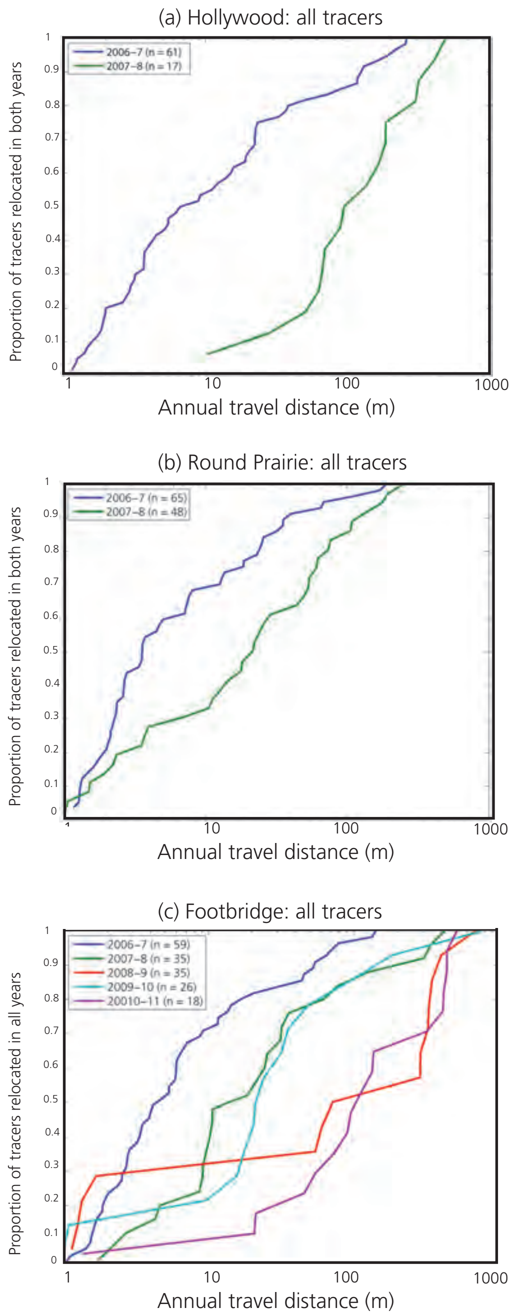

Figure 5. Statistical summary of particle path length distributions during each year for each reach. Annual travel distances for all tracers are represented using Cumulative Distribution Functions (CDF).

magnitude and duration of high flow might have allowed the tracers to take multiple hops during the runoff season. An even higher peak discharge occurred in the spring of 2010 with the greatest single displacement observed at 779 m. Although the peak discharge for 2010 was the largest during our study, the hydrograph in figure 3 indicates the period of high flow was relatively brief, suggesting particles might not have taken as many steps as in the previous year. By 2011, all but 18 of our initial tracers had been lost. Sixteen of the particles recovered in 2011 were mobile and the CDF shifted back to the right. The combination of a larger peak discharge and a longer duration of high flow might have contributed to the greater path lengths in 2011 than 2010. Moreover, the median travel distance for 2011 was roughly equivalent to the spacing between large point bars along this meandering channel. These observations were consistent with the notion that the spatial scaling of river morphology is dictated by the displacement of individual sediment particles from sites of erosion to areas of deposition.

An equilibrium channel morphology, in which a stable form is maintained by an approximate balance between sediment supply and transport capacity, is established over a period of many years. Although the annual travel distances presented in figure 5 and described above provide some sense of the relationship between path length and morphology, a slightly longer-term perspective also is helpful. To gain such a perspective, we calculated the total cumulative travel distance of each tracer over the entire period of study. These cumulative travel distances provided insight on the downstream translation of the tracers and their dispersion over time (figure 6).

Of the three sites, Footbridge was closest to an equilibrium configuration, with only gradual changes occurring from year to year. Cumulative displacements remained small through 2007 and 2008, although higher flows in the latter year expanded the distribution of path lengths. Not until 2009 did the median cumulative displacement increase to three channel widths, with the distribution becoming more symmetric as well. By the end of the study in 2011, the median cumulative travel distance had increased to about five channel widths, implying on average, particles tend to move about one channel width downstream per year. In other words, as in a race, the pack spreads out as time goes on and the stragglers fall farther and farther behind the frontrunners.

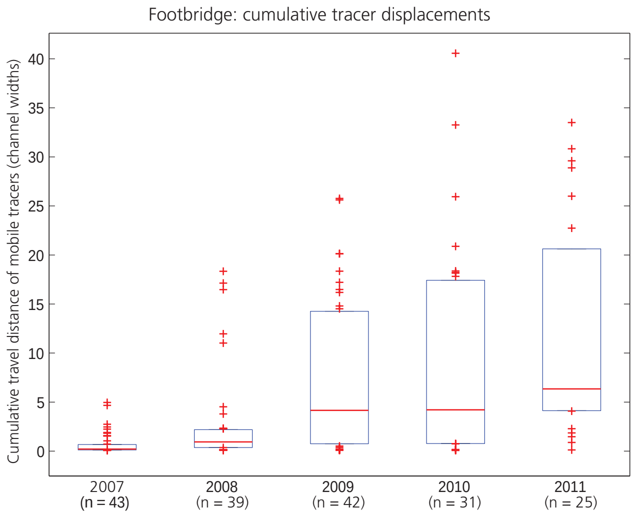

Figure 6. Cumulative travel distances of all recovered tracers for each year in the Footbridge Reach are summarized using a sequence of box plots, in which the red lines indicate the median, the blue boxes encompass the 25th–75th percentiles of each distribution, and the point symbols indicate outliers.

The Rocks Keep on Rolling

Given the limitations of this study (small sample size and low tracer recovery rates), our data support a few tentative conclusions. First, a measure of the central tendency of the distribution of particle path lengths, such as the median travel distance, scales with the point bar spacing typical of meandering channels, provided that streamflows are sufficient to mobilize and transport sediment. Second, path length distributions varied among our three study sites due to their distinct geomorphic characteristics, with greater travel distances occurring in the erosional Hollywood reach than in the depositional Round Prairie site or the relatively stable Footbridge Reach. Third, the displacement of sediment particles, both individually and in aggregate, is influenced by hydrologic conditions, primarily the magnitude and duration of the spring snowmelt, with fewer immobile tracers and greater path lengths during high runoff events. As a final, more qualitative conclusion, this tracer study illustrated the difficulty of river research. Yes, field work can be demanding, but more significant is the intellectual challenge of trying to understand the feedback between form and process that makes gravel-bed streams so dynamic, complex, and aesthetically appealing. Of course, that challenge is why studying rivers is lots of fun, too.

Literature Cited

Ashmore, P.E., and M. Church. 1998. Sediment transport and river morphology: A paradigm for study. Pages 115-148 in P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley editors, Gravel-Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, Colorado.

Lamarre, H., B. MacVicar, and A.G. Roy. 2005. Using passive integrated transponder (PIT) tags to investigate sediment transport in gravel-bed rivers. Journal of Sedimentary Research 75(4):736-741.

Legleiter, C.J., and P.C. Kyriakidis. 2006. Forward and inverse transformations between Cartesian and channel-fitted coordinate systems for meandering rivers. Mathematical Geology 38(8):927-958.

Legleiter, C.J. 2014. A geostatistical framework for quantifying the reach-scale spatial structure of river morphology: Application to restored and natural channels. Geomorphology 205:85-101.

Liébault, F., H. Bellot, M. Chapuis, S. Klotz, and M. Deschâtres. 2012. Bedload tracing in a high-sediment-load mountain stream. Earth Surface Processes and Landforms 37(4):385-399.

Meyer, G.A. 2001. Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. Geomorphology 40(3):271-290.

Pyrce, R.S., and P.E. Ashmore. 2003. Particle path length distributions in meandering gravel-bed streams: Results from physical models. Earth Surface Processes and Landforms 28(9):951-966.

Pyrce, R.S., and P.E. Ashmore. 2005. Bedload path length and point bar development in gravel-bed river models. Sedimentology 52(4):839-857.

YS

Carl Legleiter is an Assistant Professor of Geography at the University of Wyoming. He began working in Yellowstone as an undergraduate at Montana State University, and Soda Butte Creek served as the field area for his dissertation at the University of California Santa Barbara. His research focuses on river morphodynamics and the development of remote sensing techniques for characterizing fluvial systems. Legleiter is shown here with his father Floyd, who played a key role in the tracer study.

Devin Lea earned a BA in Geography from Aquinas College in Michigan and an MA in Geography from UW, where his thesis research focused on connections among channel dynamics, sediment tranport, and the spatial distribution of stream power along Soda Butte Creek.