RIVER RESEARCH AND APPLICATIONS
River Res. Applic. (2013)

FINE SEDIMENT INFILTRATION DYNAMICS IN A GRAVEL-BED RIVER FOLLOWING A SEDIMENT PULSE

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ABSTRACT

Pulses of fine sediment in gravel-bedded rivers can cause extensive fine sediment infiltration (FSI) into void spaces in coarse bed material, potentially altering river morphodynamics and aquatic ecosystems. Previous work suggests a conceptual model of FSI whereby FSI occurs to a limited depth as a function of the relative grain size of bed sediment compared with infiltrating sediment and is influenced by fine sediment supply and local flow dynamics. Our study applies this conceptual model to a complex reach of a wandering, medium-sized, gravel-bed river to investigate the spatial and temporal controls on FSI. To constrain the timing of FSI, we use the release of contaminated sediment from an upstream dam removal and complementary field methods (bulk sampling, freeze cores and infiltration bags) to capture sediment across varied depositional settings. Our results indicate that, even in a morphologically complex reach, fine-sediment content in the bed does not vary significantly among deposition settings or vertically below the bed surface. We also found that the most contaminated fine sediments released into our study river by a dam removal are not present within the bed material and that substrate has likely been reworked over the period between the release of contaminated sediment and sampling. Our observations also suggest that seals of fine sediment causing void pore space at depth, which have previously been associated with FSI, are not evident in our field area. This suggests that in natural systems, high sediment supply and mobile beds may limit seal formation and persistence. Copyright © 2013 John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

KEY WORDS: fine sediment infiltration; bulk sample; freeze core; infiltration bag; bed mobility; Clark Fork River; Milltown Dam

Received 19 July 2012; Revised 2 January 2013; Accepted 3 January 2013

INTRODUCTION

Fine sediment infiltration (FSI) occurs when sand and smaller sediment (<2 mm) are deposited into river-bed gravel and cobbles. FSI can degrade habitat for macroinvertebrates, salmonids and other aquatic organisms (Jones *et al*., 2011; Richards and Bacon, 1994; Waters, 1995) by reducing intragravel flow, decreasing oxygen availability and inhibiting oxygen exchange across embryo membranes (Greig *et al*., 2005; Suttle *et al*., 2004). Bed morphology and sediment transport dynamics can also be altered by FSI (Dietrich *et al*., 1989; Lisle and Hilton, 1999). FSI can smooth the bed, which could decrease the mobility of larger particles by limiting their protrusion (Kirchner *et al*., 1990) or by adding cohesion (Barzilai *et al*., 2012), or it could increase overall bed mobility by increasing near-bed velocities (Sambrook Smith and Nicholas, 2005). Because land uses can increase fine sediment inputs to rivers (Farnsworth and Milliman, 2003; Owens *et al*., 2005), understanding of the dynamics of FSI has management implications as well.

The occurrence of FSI depends on several linked aspects of river morphodynamics, including the size distribution of bed material, the size distribution and amount of sediment supplied to a reach, and local hydraulics. The size distribution of bed material influences the available pore space of the substrate (Cui and Parker, 1998; Cui *et al*., 2008; Leonardson, 2010; Sulaiman *et al*., 2007; Wooster *et al*., 2008). Larger grains offer more pore space to receive smaller, infiltrating grains, yet a wide range of grain sizes can result in less pore space because of void filling by variably sized grains (Figure 1) (Cui and Parker, 1998; Wooster *et al*., 2008). The ratio of the size of the bed gravel to the size of the infiltrating material also influences the fine sediment fraction (Lisle, 1989; Gibson *et al*., 2011; Leonardson, 2010). Larger infiltrating grains can be trapped among the pore spaces of large bed grains near the surface of the substrate, thereby blocking infiltration deeper into the substrate and creating a seal (Leonardson, 2010; Lisle, 1989) or bridge (Gibson *et al*., 2010). Seal formation as a result of FSI has been observed in both laboratory and field studies (Acornley and Sear, 1999; Beschta and Jackson, 1979; Frostick *et al*., 1984; Gibson *et al*., 2010; Lisle, 1989). Gibson *et al*. (2010) suggest that seals or bridges form where the ratio $D_{15\ \mathrm{substrate}}/d_{85\ \mathrm{infiltrating\ sand}}$ is below 12–14.

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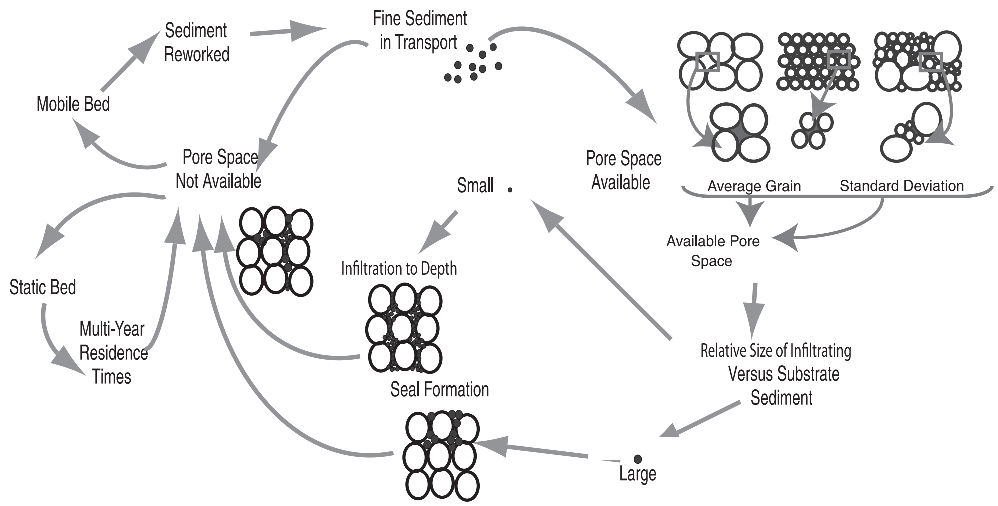

Figure 1. Conceptual model of fine sediment infiltration, whereby (i) fine sediment in transport can only infiltrate if its settling velocity exceeds shear velocity and pore space is available; (ii) the amount and depth of infiltration depends on the relative size of substrate and the infiltrating fine sediment; and (iii) residence time of fine sediment in the bed depends on the frequency and depth of bed mobilization

Hydraulics, sediment transport dynamics and bed mobility also affect FSI. The magnitude and spatial variability of sand supply and transport influence FSI, with zones of active sand transport producing the most rapid saturation of the bed with fines (Wooster *et al*., 2008). High FSI has been associated with zones of low depth and scour potential (Schindler Wildhaber *et al*., 2012), high velocity (Frostick *et al*., 1984) and slack water (Carling and McCahon, 1987) areas. Lisle (1989) highlighted the importance of scour and fill events in depositing sand layers, winnowing fines from the bed and exposing deeper portions of the bed to FSI. Lisle (1989) also found that the largest proportion of infiltrated sediment originated from the finest fraction of bedload rather than from settled suspended load. Less frequently mobilized bed materials can harbour fines with longer residence times (Venditti *et al*., 2010), although the mobility of coarse surface layers (e.g. Vericat and Batalla, 2006) and associated feedbacks with infiltrated fines are poorly understood. The work described earlier suggests a conceptual model whereby FSI is determined by the relative grain sizes of coarse bed material compared with the fine-grained sediments, can be depth limited as a result of seal formation and depends on spatial variability in sand supply, hydraulics and bed mobility (Figure 1).

A fundamental challenge of understanding FSI is how to measure it in the field. Previous workers have measured infiltration and/or the fine sediment content of bed materials using, for example, concrete-lined pits with lids of variably sized framework gravels (Frostick *et al*., 1984), infiltration cans with solid walls and a tri-axial freeze core sampler (Lisle, 1989), a hybrid McNeil sampler-freeze core system (Rood and Church, 1994) or combinations of these methods (Schindler Wildhaber *et al*., 2012). Other methods such as magnetic resonance imaging of sediments (Haynes *et al*., 2009) and hand-held suction devices for drawing unconsolidated sediments into a collector (Turner *et al*., 2011) also hold promise for infiltration measurements. Most of these methods, however, can produce biased results or otherwise have drawbacks (Kondolf *et al*., 2003; Zimmermann *et al*., 2005; Zimmermann and Lapointe, 2005), particularly with respect to deployment in larger rivers.

In this study, we investigate the conceptual model of FSI described earlier by supplementing traditional measurement methods with geochemical tracing of fine sediments, in a field setting that is large and geomorphically complex relative to rivers considered in previous FSI studies. We do so by taking advantage of and drawing motivation from the release and downstream transport of a dam-removal-induced pulse of metal-rich fine sediment. The 2008 removal of Milltown Dam, from the confluence of the Clark Fork River (CFR) and Blackfoot River, Montana, released several hundred thousand cubic metres of fine sediment into the gravel-bedded CFR. As reviewed further later, this sediment consisted of both mining-derived sediments with elevated metals concentrations from the Clark Fork arm of Milltown reservoir and uncontaminated sediments from the Blackfoot arm of the reservoir. Since the start of dam removal activities, we have observed extensive FSI in the bed of the CFR. Even as fine sediments that were deposited on bars and banks of the CFR following the 2008 dam breach were mobilized and transported downstream in the years following their initial deposition, we observed, qualitatively, persistently high fine sediment concentrations in the gravel interstices. This led us to conduct an investigation of FSI that seeks both to test the conceptual model of FSI described and to understand the response of the CFR to the Milltown sediment pulse.

In particular, we investigate three questions. First, what is the spatial variability of FSI according to depositional setting and vertically in the bed, and what does this indicate about hydraulic and morphologic controls on where FSI is most likely? Second, what is the source of FSI in our study area: do infiltrated fines bear the metals signature of contaminated sediment released following the recent dam removal, or are they geochemically similar to cleaner tributary sources? Third, what is the residence time of infiltrated fine sediment, and what does this indicate about both the persistence of contaminant infiltration and about whether FSI produces static or dynamic beds in gravel-bed rivers?

STUDY AREA

Our study site is a 1-km reach of the CFR that is located 16 km downstream of the former Milltown Dam site (Figure 2). Immediately upstream of this reach, the river transitions from having a single thread and high transport capacity, partly as a result of levees through the town of Missoula, to a wandering, multithread planform. We observed significant, post-dam removal sediment deposition in this reach of the CFR, including side channels, floodplains, bars and banks. Our reach has an average slope of 0.002, a width at baseflow of ~50 m, a mean annual flow of 83 $m^3 s^{-1}$ [United States Geological Survey (USGS) Clark Fork above Missoula gage #12340500] and a drainage area of 15 800 km^2 (Figure 2). The study reach includes a pool-riffle main channel, two side channels and two mid-channel bars/islands in the zone where the three channels converge (Figures 2 and 3). The resulting flow bifurcations and convergences produce spatially varied hydraulics.

Milltown Dam was built on the CFR, immediately downstream of its confluence with the Blackfoot River, in 1907. In 1908, a 500-year flood deposited millions of cubic metres of sediment behind the new dam, including tailings derived from upstream mining activities (Moore and Luoma, 1990). Milltown Dam and its reservoir stored five million cubic metres of sediments that caused arsenic contamination of local groundwater and carried a unique metal signature, with arsenic, copper, lead and zinc concentrations above background levels (Andrews, 1987; Johns and Moore, 1985; Moore and Woessner, 2003; Moore *et al.*, 1988). For example, copper concentrations in sediment averaged 2300 ppm in the most contaminated portion of the Clark Fork arm of the reservoir and 1300 ppm in an upstream portion of the Clark Fork arm (Envirocon, 2004). Ice jams in 1996 released contaminated sediment downstream and caused concern about the structural integrity of the dam (Moore and Landrigan, 1999). The dam was removed as part of a multi-year remediation and restoration effort (US EPA R8, 1996) involving progressive reservoir drawdowns, excavation of two million cubic metres of contaminated sediment from the reservoir and breaching of the dam in March 2008.

The dam removal resulted in reservoir erosion, and downstream sediment and metals transport at rates that peaked in 2008, following the March 2008 breach, before declines in subsequent years (Figure 4) (Sando and Lambing, 2011). Between the start of a permanent drawdown of Milltown reservoir in June 2006 and the dam breach, 140 000 t of suspended sediment, 44 t of copper and 6.4 t of arsenic were eroded from the reservoir and transported downstream. In 2008 and 2009, following the dam breach, 420 000 t of suspended sediment, 169 t of copper and 15.8 t of arsenic were eroded (Sando and Lambing, 2011). Other trace metals

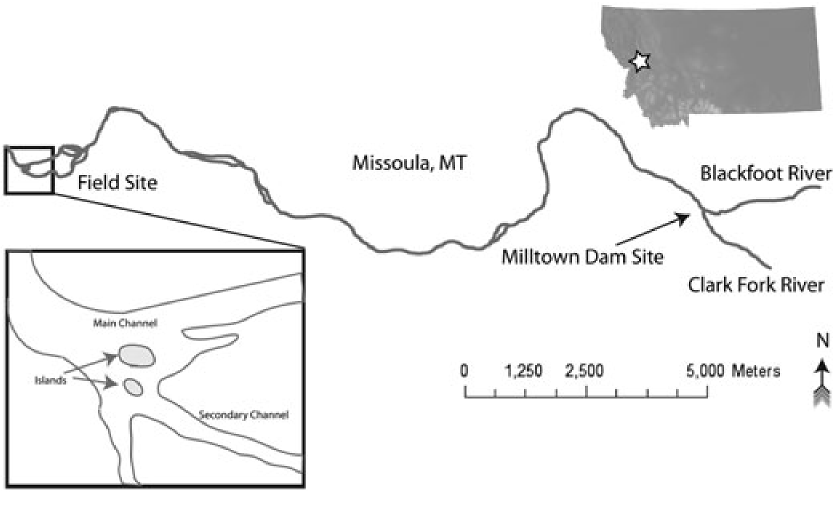

Figure 2. Location map showing field site on the Clark Fork River (flow is to the west), the site of the Milltown Dam, close up of the field site, and location within Montana

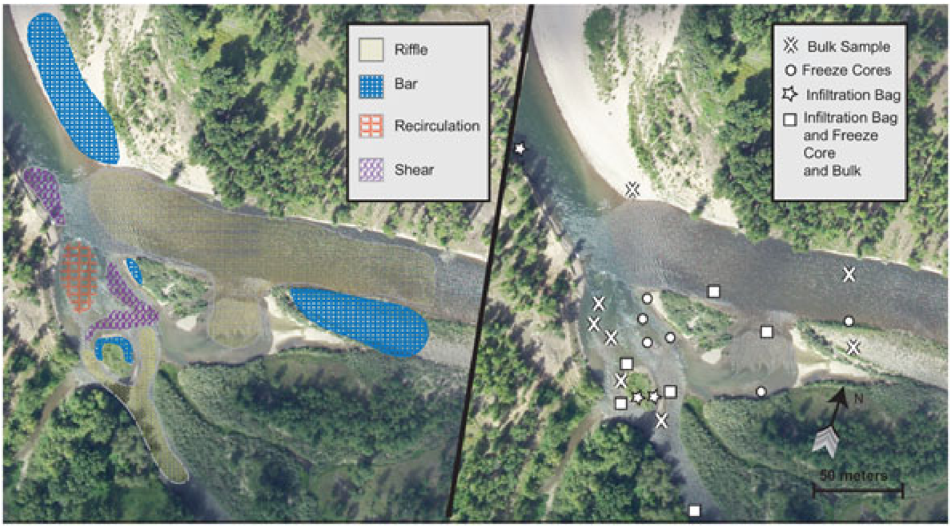

Figure 3. Aerial photograph of field site: left side shows delineation into four hydraulic and depositional settings (riffle, bar, recirculation zone and shear zone) by which sampling was organized; right side shows sample locations for bulk samples, freeze cores and infiltration bags (R. Hauer photo, August 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

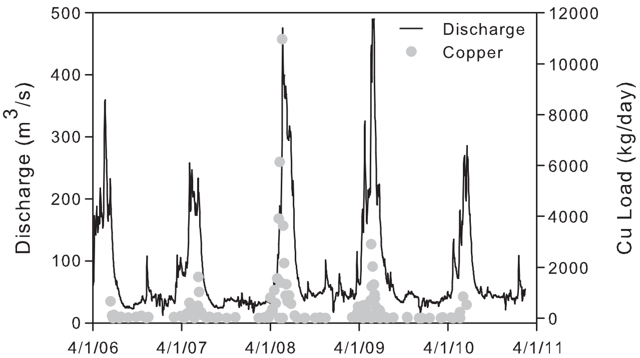

Figure 4. Discharge and copper load for a multiyear period surrounding the 28 March 2008 breach of Milltown Dam, as measured at United States Geological Survey Clark Fork above Missoula Gage (#12340500). Other metals of interest (As, Pb and Zn) have different concentrations but generally follow the same trend

(e.g. cadmium, zinc and lead) followed similar patterns to copper. In 2010, the year of our field measurements, 21 000 t of suspended sediments were exported from the reservoir. As part of the analysis presented here, we relate the metals transport in the CFR in the years since the dam breach, expressed in terms of concentrations rather than loads, to the concentrations measured in our field site.

METHODS

We sampled sediments in four categories of hydraulic and depositional settings in our study reach: (1) riffles (high-velocity, high transport capacity areas); (2) shear zones (areas of flow separation typically associated with wakes and/or flow convergence); (3) recirculation zones (areas distinct from the previous category by virtue of lower velocities and strong lateral and/or upstream flow components); and (4) lateral bars (subaerial at baseflows but submerged at high flows) (Figure 3). We used three methods to collect sediment samples for analysis of grain size and/or metals concentrations: bulk sampling, freeze cores and infiltration bags (Figure 5). These samples were collected in 2010.

To characterize the grain size distribution of the substrate, we collected bulk samples using a modified McNeil sampler (McNeil and Ahnell, 1964; Shirazi and Seim, 1981) with a 26-cm core barrel diameter that penetrated the bed to a depth of ~15–25 cm (Figure 5(a)). Bed material was collected by working the McNeil sampler into the substrate, until the base of the basin was level with the bed, and scooping grains that were at least 50% enclosed in the core by hand into the larger collecting basin. A lid was then placed over the core's opening to limit loss of fines, after which the sampler was removed from the substrate, allowing water inside the sampler to drain but retaining the sediment sample. Pairs of samples were taken within 1 m of each other and were composited into single samples. Twenty-one samples, ranging in weight from 13 to 30 kg, were collected. Coarse substrates, heavy samples and flows created challenging conditions for collecting sub-aqueous bulk samples, resulting in some loss of fine sediment (see Zimmermann *et al.* 2005 for further discussion of such problems).

Bulk samples were sieved with a Ro-Tap and Gilson tray shaker at half-phi intervals (−6 to 4 phi, 0.063–64 mm) to determine size distributions. Large bed particles, as were abundant in our field site, can both skew grain size distributions, in the absence of very large samples, and present

DOI: 10.1002/rra

Figure 5. Field methods used to measure bed material composition and collect samples for metals analysis: (a) modified McNeil sampler; (b) tri-axial freeze core set-up with 30L nitrogen tank, boat and tripod (also see Supporting information); (c) example freeze core; and (d) hand-sewn infiltration bag. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

difficulties for collection of integral, underwater substrate samples (Church *et al*., 1987; Rood and Church, 1994). We therefore, for calculation of the fine-sediment content of bulk samples, truncated our size distributions by eliminating grains larger than 32 mm, a threshold selected on the basis of the sample volumes and largest grains present (after Adams and Beschta, 1980; Church *et al*., 1987; Rood and Church, 1994). Fine-sediment content was calculated as the fraction by weight of the truncated sample <2 mm (after Rood and Church, 1994). We also present the full, untruncated size distributions and their geometric means, acknowledging the bias therein produced by large grains. To evaluate the effect of depositional setting on fine-sediment content, we completed an analysis of variance in which the variation among samples within each depositional setting type (riffle, shear zone, etc.) was compared with the variation between groups. The absence of pre-2010 data on bed material sizes in our study site precluded testing of the effect of the dam removal on fine-sediment content.

Freeze cores were used to acquire samples for metals analysis and to investigate the depth and stratigraphy of infiltration. Thirteen freeze core samples were collected using a tri-axial freeze coring device (after Everest *et al*., 1980; Lisle, 1989). The tri-axial freeze core sample poles were pounded as deep as possible into the substrate using a sledgehammer, liquid nitrogen was inserted to freeze sediment to the pole of the injection rods and the sample was removed using a tripod and hand winch (Figure 5(b); Supporting information). An inflatable cataraft was used to transport the liquid nitrogen tank (which weighed ~100 kg and needed to be kept upright) and sample apparatus to sample locations. Sample weights ranged from 1.3 to 4 kg of sediment per core, and sample depths varied between 30 and 70 cm (e.g. Figure 5(c)). Sections were scooped into bags at 10-cm depth intervals as the sample melted. Fine sediment was then analyzed for metal content as described later. In addition, to test for vertical variability of fine-sediment content and to evaluate whether fine-sediment seals were present in the upper layers of the bed material, we sieved each depth interval for the seven best-quality (in terms of depth and volume) freeze cores. We then calculated the fine-sediment content (<2 mm) as the fraction by weight of each interval, after truncation of samples at 32 mm to limit bias caused by large clasts, as for the bulk samples. We tested for differences in fine-sediment content with depth using analysis of variance.

Thirty-four infiltration bags (Figure 5(d)) were installed in the river bed in early 2010 to collect infiltrating fine sediment (Lisle and Eads, 1991) for geochemical analysis. To install infiltration bags, a bulk sample was collected with the McNeil sampler, leaving a circular excavation pit that was maintained by leaving the McNeil in place. A collapsed infiltration bag was placed within the excavation pit. The extracted bulk sample was field sieved to separate sediment <2 mm, the remaining coarser grains were returned into the collapsed bag in the excavation pit and the McNeil sampler was removed. The sediments returned to the infiltration bags were composed primarily of gravels, with geometric means and standard deviations for different infiltration bags ranging from 33 ± 3 to 43 ± 3 mm. Infiltration bags, which were retrieved in late summer 2010, therefore allowed collection of fine sediment that infiltrated during the 2010 hydrograph. Because many of the bags were scoured during 2010 high flows, the infiltration bags also, inadvertently, provided information on bed mobility.

We also investigated bed mobility by placing tracer gravels in several riffle locations. These comprised two groups, each painted a different, high-visibility colour: 7 kg of ~4 mm gravel and 18 kg of ~16–32 mm gravel. The tracer gravels were added to the bed in October 2009 and subsequently monitored to determine bed mobility or lack thereof. To develop insight into the hydraulic conditions influencing sediment transport and deposition, we calculated boundary shear stresses for 2010 high-flow conditions ($\tau_o = \rho g h S$, where ρ is water density, g is gravitational acceleration, h is flow depth and S is slope). Slope and depth data were derived from topographic surveys and pressure transducers

DOI: 10.1002/rra

installed at the upstream and downstream ends of the study reach. Boundary shear stress was compared with the critical shear stress (τ_c) for mobilization of our tracer gravels, assuming a dimensionless critical shear stress (θ) of 0.045 (Church 2006), where $\tau_c = \theta(\rho_s - \rho)gD$; ρ_s is the sediment density and D is the grain size.

To fingerprint our field samples and to evaluate them in the context of sediment and metals transport associated with the Milltown dam removal, we analyzed 72 sediment samples for concentrations of As, Cu, Pb and Zn. Ten samples were from infiltration bags, and 62 were from freeze cores (including stratigraphic subdivisions of our 13 freeze cores). The sediment <2 mm from these samples was analyzed for metal content using Inductively Coupled Argon Plasma Optical Emission Spectrometry (ICP-OES) at the University of Montana Environmental Biogeochemistry Lab. Samples were oven-dried for 24 h and thoroughly mixed. A portion of each sample was removed and ground using a ball mill in a zircon vial, and then 0.4 g of the ground sample was acid digested using EPA Method 3050B (US EPA R8, 1996). Digests were then analyzed using ICP-OES EPA Method 200.7. Quality control samples were analyzed in accordance with method requirements to determine precision and accuracy. Average (±standard deviation) duplicate digestion and analysis of samples differed by 4.7 ± 2.8% (As), 6.2 ± 9.9% (Cu), 7.2 ± 4.6% (Pb) and 4.8 ± 1.3% (Zn). Average (±1 standard deviation) recoveries for standard reference material NIST SRM 2710–Montana Soil (NIST, 2002) were 91.4 ± 0.9% (As),100.8 ± 3.6% (Cu), 80.8 ± 2.4% (Pb) and 81.8 ± 4.4% (Zn). Method spike recoveries ranged from 84% to 98% (As), 83% to 95% (Cu), 95% to 116% (Pb) and 83% to 103% (Zn).

Variations in the size distribution of the finest sediment fractions in our samples may have biased metals concentrations; smaller grains are more likely to have higher metals concentrations (Horowitz, 1985). Such variations may have arisen as a result of both spatial variability among samples and variability between the methods. Infiltration bags would be expected to retain a greater fraction of fine sediments than freeze cores because in the former method, sediments are enclosed in a bag as they are extracted from the bed, effectively preventing loss of fines. Freeze cores, in contrast, are subject to disturbance of the substrate when sample poles are pounded into the substrate and are exposed to the flow as they are extracted, relying only on the ‘frozen’ nature of the sample to prevent loss of fines (e.g. Kondolf *et al.*, 2003). To account for size-variability effects, we normalized the concentrations of As, Cu, Zn and Pb in the freeze cores and infiltration bags to the aluminium concentration, as a surrogate for grain size (Förstner and Salomons, 1980; Horowitz, 1985; Schropp *et al.*, 1990). A nominal value of 15 000 ppm Al was used for normalization because the typical value for Al in fine-grained (<0.063 mm) bed surface sediments in this area (collection of which is described later) was 14 537 ± 1778 ppm.

We tested the spatial variation in metals concentrations for all freeze core samples, both vertically (with depth in the substrate) and laterally (with depositional setting). We performed a two-way analysis of variance in which the two factors were depth below the surface (with 10 cm increments as levels) and depositional environment (riffles, shear zones and recirculation zones as levels). To account for grain size variability, we used normalized metals concentrations (As, Cu, Pb and Zn) as the response variables (analogous tests on raw metals data produced similar results as those for normalized metals).

To develop insights into the timing and duration of FSI in our field site, we also compared the metals concentrations of fine sediment in our field samples with other samples collected along the CFR at our site and within a few river kilometres upstream and downstream. Fine-grained sediment (<0.063 mm) samples were collected from lateral areas of the channel on five different days from May to August 2008 (Garcia, 2012) and on 15 March 2011. For these samples, sediment was collected from the top 1–3 cm of surficial deposits, sieved through a 0.063-mm nylon filter into a plastic bottle, stored on ice and returned to the laboratory for measurement of metals concentrations. These data facilitate interpretation of the FSI data by illustrating metals concentrations in fine-grained bed sediment during two time windows: shortly after the dam removal, in 2008, and then after our 2010 freeze core and infiltration bag sampling, to which we consider the March 2011 surficial sediment samples to be temporally comparable because there were no high-flow events between these sampling periods. The fine-grained bed sediment data also provide a means to normalize our metals concentrations for variability in fine-sediment content.

Another means of evaluating our metals concentrations is by comparison with measurements by the USGS from the Clark Fork above Missoula Gage (NWIS, 2012), which is 13 km upstream of our field site. To determine the metals concentrations of suspended sediment passing this gage, we subtracted the filtered-recoverable metal concentration in the water from the unfiltered-recoverable metal concentration and normalized to total suspended sediment concentration (after Sanding and Lambo, 2011). The resulting solid-phase metals concentrations (in ug g^{-1} or ppm), by illustrating temporal trends in concentrations since the Milltown dam removal, provide context for our interpretations of the source and residence time of fine sediments in the bed.

RESULTS

Spatial variability of bed material composition

Bulk samples showed that, among depositional settings, bed materials were coarsest in riffles, where cobbles comprised

DOI: 10.1002/rra

Table I. Mean, minimum and maximum of geometric means and fraction of fine sediments (<2 mm) for bulk samples, grouped by depositional settings

Depositional setting	n	D_g			Fine sediment fraction		
		Mean	Min	Max	Mean	Min	Max
Riffle	8	55	31	128	0.13	0.04	0.24
Shear zone	8	34	19	45	0.12	0.03	0.21
Recirculation zone	3	26	17	33	0.17	0.09	0.25
Bar	2	33	23	42	0.11	0.03	0.18

Geometric means are calculated from our full samples, whereas the fine sediment fractions are calculated after truncation of samples at 32 mm.

the dominant size fraction by weight and that shear zones, recirculation zones and bars were dominated by medium to coarse gravels (Table I; Figure 6). The D_{84} for most of our samples is on the order of 10^2 mm, suggesting that the coarser tail of framework bed material in our field area provides ample accommodation space for FSI. The fraction of fine sediment (<2 mm) in our bulk samples ranged, after truncation at 32 mm, from 0.03 (in a shear zone sample) to 0.23 (in a recirculation zone). Variability in the fine-sediment content among samples within each setting was substantial (Table I; Figure 7), and the difference in fine-sediment content among depositional settings was not statistically significant ($p = 0.72$). Among the sediments finer than 2 mm, the most commonly occurring were in the 0.35–0.5-mm range in all depositional settings.

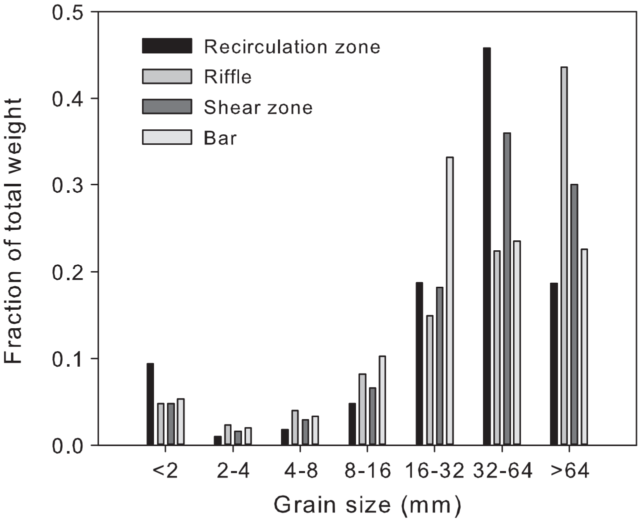

Figure 6. Grain-size distributions for bulk samples, as fraction of sample weight, composited by depositional setting

Freeze cores provided information on the vertical variability in grain sizes. For example, Figure 8(a) shows, for a freeze core collected in a riffle, sediments distributed across sand, gravel and cobble fractions with depth but no systematic downward fining or coarsening. Comparison of the fine-sediment content of different depth intervals, intended to evaluate whether greater sand fractions occurred at the surface in a manner indicative of seal formation, found that the fine-sediment fractions did not differ significantly with depth ($p = 0.15$), despite their tendency to be higher at greater depths below the bed surface (Figure 8(b)).

Similarly, analysis of the vertical variability in metals concentrations in freeze cores indicated that differences with depth are non-significant for all metals ($p = 0.31$, 0.38, 0.4 and 0.13 for As, Cu, Pb and Zn, respectively). Figure 9 shows the depth profiles of metals concentrations for the six freeze cores collected in riffles. Among depositional settings, differences in metals concentration in freeze cores were non-significant for As, Cu and Pb ($p = 0.41$, 0.07 and 0.25, respectively) and marginally significant for Zn ($p = 0.048$).

Source and residence time of infiltrated fine sediments

Figure 10 shows the distribution of both the ‘raw’ and ‘normalized’ metals concentrations (As, Cu, Pb and Zn) from the freeze cores and infiltration bags (raw metals concentrations are also summarized in Table II). Metals concentrations are also shown for fine-grained (<0.063 mm) bed sediment from samples collected in March 2011. Sediments from freeze cores averaged lower metal concentrations than those collected using infiltration bags, and the concentrations in bed-material samples are slightly higher still (Figure 10). As

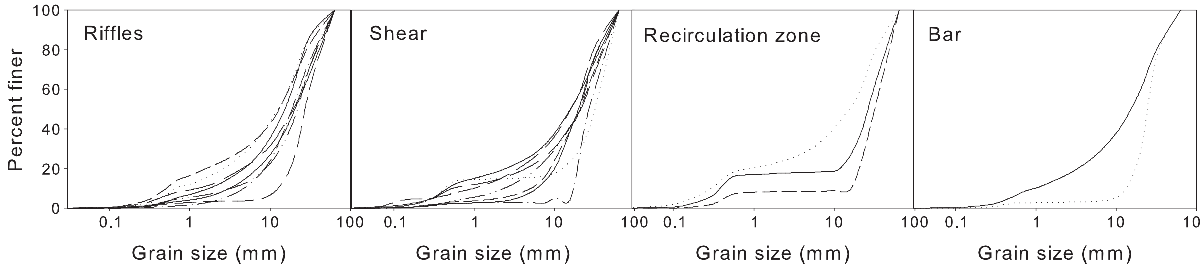

Figure 7. Grain size distributions for bulk samples, grouped by depositional setting and truncated at 32 mm

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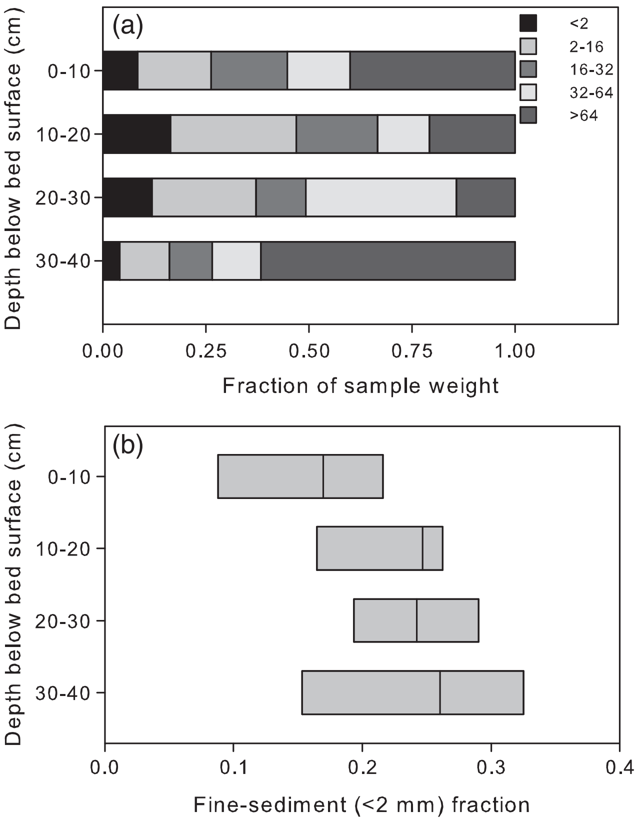

Figure 8. Grain-size variation with depth below bed surface: (a) size distribution, as fraction of sample weight at each depth interval, for example freeze core collected from a riffle, and (b) distribution of fine-sediment fractions for seven freeze cores at different depth intervals, calculated as fraction of sediment <2 mm after truncation of samples at 32 mm to limit bias caused by large clasts. Vertical variability in fine-sediment content with depth is not significant; these results suggest that fine-sediment seals are not present

noted previously, differences among methods in retention of fines or in the size fractions analyzed for metals (<2 mm for freeze cores and bags and <0.063 mm for surficial bed sediments) may contribute to variability in metals concentrations. After normalization of the metals data to account for the possible effect of grain-size variations, the Cu, Pb and Zn concentrations from the infiltration bags and bed-material samples are similar.

To contextualize the metals concentrations we measured, Figure 11 shows a time series of the solid-phase copper concentrations we calculated from USGS water quality and suspended sediment data and of the copper concentrations from surficial bed-sediment samples collected in the vicinity of our field site in 2008 (Garcia, 2012) and March 2011. Figures 10 and 11 show that the concentrations measured in our field site in March 2011 are far lower than the peak, post-breach concentrations recorded in spring 2008 in both the USGS suspended sediment and bed-sediment samples. Those 2008 data show concentrations similar to those found in contaminated Milltown sediments. The lower copper concentrations in the 2010 and March 2011 sediments suggests that these sediments are derived from different sources than the most contaminated sediment released from Milltown reservoir.

The metals data are consistent with other lines of evidence about the bed mobility in our study reach and attendant effects on fine-sediment content. Our tracer gravels were displaced during the 2010 runoff hydrograph, indicating that at least portions of the bed surface had been mobilized. This is consistent with calculations showing that the reach-average shear stresses associated with 2010 high flows exceeded the critical shear stress for mobilization of our tracer gravels. At the 2010 peak discharge of 286 $\mathrm{m^3\,s^{-1}}$ (1.5-year recurrence interval), the reach-average flow depth (1.5 m) and slope (0.002) suggest $\tau_o = 29\,\mathrm{N\,m^{-2}}$. The critical shear stress (τ_c) for our tracer gravels ranges from 3 $\mathrm{N\,m^{-2}}$ for the 4 mm gravels, to 12 $\mathrm{N\,m^{-2}}$ for the 16 mm gravels, to 23 $\mathrm{N\,m^{-2}}$ for our largest (32 mm) gravels. Further evidence of bed mobilization is provided by the disappearance of many of our infiltration bags. Of the 34 bags we installed, only 13 were recovered, suggesting scour to a depth of 20–30 cm (the depth to which bags were installed).

DISCUSSION

This study investigated the spatial variation in FSI as a function of depositional settings, the source of fine sediment with respect to a recent dam removal and the residence time of fine sediment in the bed. Further, we evaluate the validity of the conceptual model of FSI shown in Figure 1 in the context of a large, complex fluvial system.

We anticipated variation in fine-sediment fractions among depositional settings, consistent with Lisle's (1989) finding that transport mode, local hydraulics and channel change affect FSI at small spatial scales. Shearing flows produce size segregation of bed materials as a result both of percolation of finer particles into the bed when coarse materials are immobile and of 'kinematic sieving' of particles when the bed is mobile (Frey and Church, 2009; Gibson *et al.*, 2009). Our field site was selected in part because of its hydraulic and morphologic complexity (Figure 3), including a range of shear and recirculation zones associated with converging and diverging flow around bars, side-channel confluences and islands. Local shear stresses capable of maintaining fines in suspension and of mobilizing coarse bed materials are likely highest in riffles, and intergravel flow that can redistribute fine sediment is also likely strongest in these areas. On the other hand, sediment that is carried in suspension in the main channel may be likeliest to become available for infiltration upon entering recirculation zones.

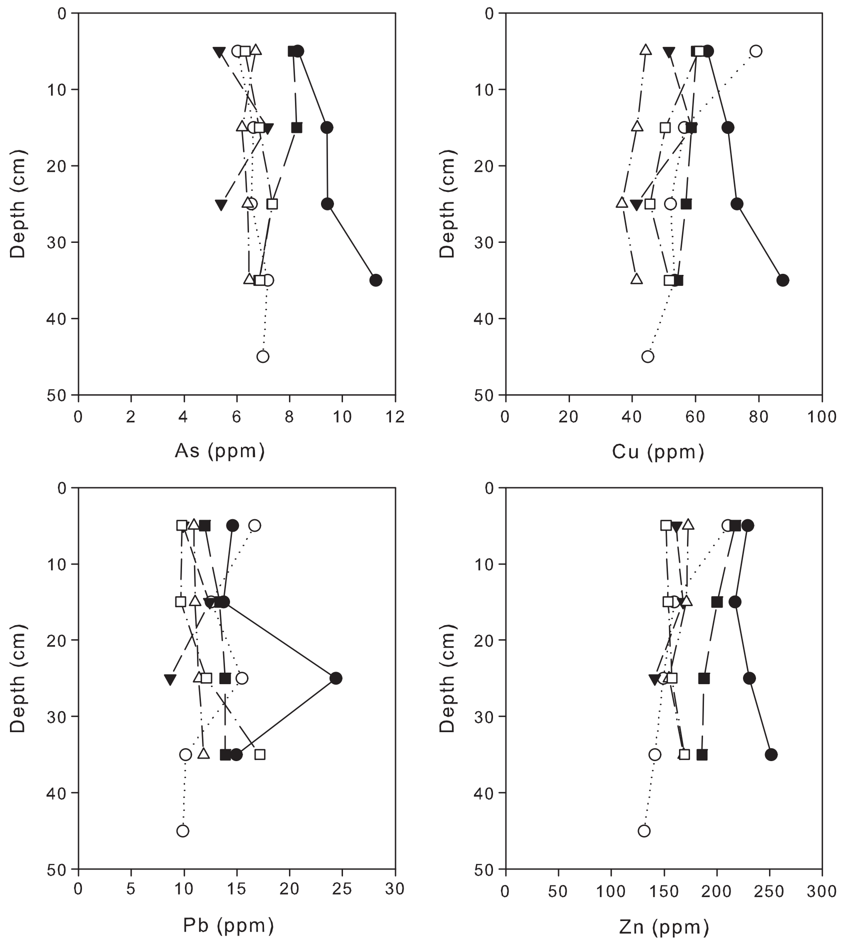

Figure 9. Arsenic, copper, lead and zinc concentrations versus depth below the bed surface for six freeze cores collected in riffles (each line represents a different riffle location) and stratified by depth. Differences in metals concentrations with depth are non-significant for all metals, whether for the riffle samples shown here or for samples from other depositional environments (shear and recirculation zones)

Differences in fine-sediment fractions among depositional settings were not statistically significant, however. The lack of significance is likely partly attributable to the small number of samples within some of the depositional settings and is also suggestive that fine-sediment fractions have less spatial variation, even within a geomorphically complex reach, than we expected. In gravel-bed rivers, there can be considerable variability of both the central tendency and of the finer tail of the grain size distribution within similar depositional settings (Rice and Church, 1998). Further, as discharge increases in our field site during high-flow conditions, areas that are hydraulically different under the baseflow conditions at which our field measurements were completed may become less distinct (e.g. Keller and Florsheim, 1993). In addition, although our focus here is on FSI, some of our samples may contain fine sediment that deposited in mixed sand and gravel packages during fill phases (Lisle, 1989) rather than by infiltration of fines into pore spaces in the gravel. Multidimensional flow modelling would permit a more complete assessment of the relationship between depositional settings, local hydraulics and FSI.

Vertical variation in fine-sediment content represents another spatial dimension of interest. On the one hand, gravel-bed rivers often have coarse surface layers and finer subsurface sediments (Parker and Klingeman, 1982), but on the other hand, seals produced by FSI have been observed in the field (Frostick *et al*., 1984, Acornley and Sear, 1999, Lisle, 1989) and laboratory (Gibson *et al*., 2010) or explained by theoretical models (e.g. Leonardson, 2010). To evaluate whether conditions in our field site were conducive to seal formation, according to the suggestion by Gibson *et al*. (2010) of a threshold between bridging and static percolation behaviour at $D_{15\ \mathrm{substrate}}/d_{85\ \mathrm{sand}} = 12\text{–}14$, we calculated this ratio for our McNeil bulk sample data. The ratio D_{15}/d_{85} among bulk samples was on average higher than the threshold for seal formation but showed high variability (mean = 24 ± 17). For bulk samples from riffles, the average D_{15}/d_{85} was 13 ± 4, within the range for potential seal formation (Gibson *et al*., 2010).

DOI: 10.1002/rra

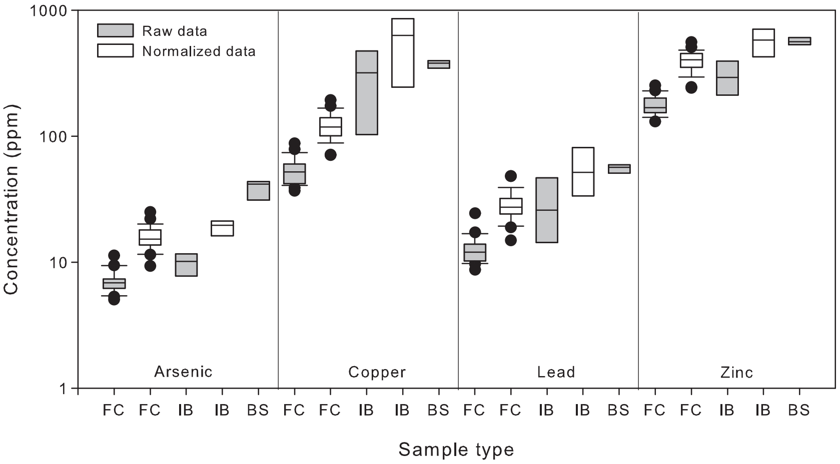

Figure 10. Distributions of concentrations of arsenic, copper, lead and zinc for sediments collected in freeze cores (FC, riffle samples), infiltration bags (IB), and March 2011 surficial bed sediments (BS). Boxes represent 25th to 75th percentile and whiskers 5th to 95th percentile. Both raw and normalized metal concentrations are shown, where concentrations from freeze cores and infiltration bags have been normalized by the aluminium concentrations of the BS samples to account for grain-size effects. The BS samples shown here for Cu are the same as the March 2011 surficial sediment samples shown in Figure 11

Table II. Mean and standard deviation of arsenic, copper, lead and zinc concentrations (ppm) in sampled sediments, grouped by sample method and depositional setting[a]

Method and setting	*n*	As	Cu	Pb	Zn
Freeze core	62	7.2 ± 1.8	66 ± 24	16 ± 11	193 ± 52
Riffle	24	7.2 ± 1.4	56 ± 13	13 ± 3.3	172 ± 33
Shear zone	29	7.3 ± 2.2	71 ± 27	18 ± 15	197 ± 51
Recirculation	9	6.8 ± 1.3	79 ± 31	15 ± 3.8	237 ± 70
Infiltration bag	10	10 ± 2.9	250 ± 165	26 ± 13	287 ± 87
Riffle	6	10 ± 3.3	305 ± 190	29.6 ± 16	282 ± 105
Shear zone	3	9.1 ± 2.2	132 ± 47	19 ± 16	274 ± 66
Recirculation	1	13	269	25	353
Bed-sediment sample[b]	6	38 ± 6.8	369 ± 50	55 ± 5.9	578 ± 63

[a] The values shown here are ‘raw’ metals concentrations; Figure 10 also shows these data after normalization by aluminium concentration to account for grain size variations.

[b] Bed-sediment samples are from March 2011.

Our freeze cores showed no evidence of seals, however. Statistical analysis of vertical variability in fine-sediment content showed that sand was not more prevalent near the surface and visual inspection of freeze cores did not find evidence of void pore space at depth. The absence of vertical variation in metals content is also inconsistent with the presence of an FSI-induced seal: either sediments are well mixed with depth or different depositional events with similar metals content are recorded. The absence of seals may have resulted from high sediment supply associated with the dam removal, as well as successive high flows that mobilized substrate to below the depth of typical infiltration, which is usually limited to a few median grain size diameters (Wooster *et al*., 2008).

In our field area, understanding both the source of fine sediments in the bed and their residence time is particularly important in light of the pulse of contaminated fine sediments associated with the Milltown Dam removal and the duration of associated downstream impacts. This also relates to the broader question regarding fine sediment in gravel beds of whether beds are frequently mobilized, such that observed fine sediment is the result of falling-limb deposition, or whether beds are immobile, such that observed fine sediment has multiyear residence times.

High metals concentrations were recorded in the CFR following the breach of Milltown Dam in 2008, both in USGS suspended sediment measurements, which showed declines after the spring 2008 peak (Figure 11), and in 2008 measurements of deposited fine sediments (Garcia, 2012). The metals concentrations of our 2010 and 2011 samples, however, suggest that the fine sediment in the bed of our field site originates from different sources than the most

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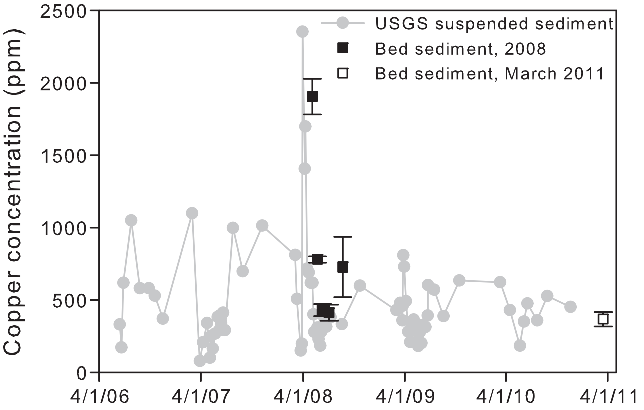

Figure 11. Copper (Cu) concentrations in sediment in the Clark Fork River, including solid-phase concentrations (calculated using United States Geological Survey water quality and suspended sediment data from the Clark Fork above Missoula gage) and mean and standard deviation of Cu concentrations from surficial (bed) sediment samples collected in the vicinity of our field site. Bed sediment samples are from 2008 (Garcia, 2012), following the breach of Milltown Dam in March of that year, and March 2011, which are the same as the BS samples for Cu shown in Figure 10

contaminated sediment released from Milltown reservoir and that sediments deposited from the 2008 metals pulse have been transported downstream or mixed with cleaner sediment.

Although our results do not definitively constrain the residence time of fine sediment in the bed, several interpretations can be advanced. The low metals concentrations in our freeze cores suggest that fine sediment deep in our freeze core samples may predate the Milltown pulse in 2008. When the Milltown contaminants travelled through our reach in 2008, we know that some deposition of fine grains with high metals concentrations occurred, as shown by the 2008 bed-surficial samples. Deposition may have been limited in the active channel, however, as a result of suspended transport of fine-grained sediments with low settling velocities. Moreover, at the time of the 2008 sediment pulse, pore space may have already been too full of fine sediment to accommodate additional FSI. These interpretations imply a static bed, with a multiyear residence time for infiltrated sediments, particularly at greater depths below the surface.

Alternatively, FSI may have occurred in 2008 but may have then been erased by substrate reworking in 2009, with new FSI, composed of less-contaminated sediments, occurring on the falling limb of the 2009 event. This ‘dynamic bed’ interpretation, with more recent FSI, and thus shorter residence times in the substrate, is supported by the evidence presented earlier of substrate reworking in 2010 and well mixed substrates with depth. In 2008 and 2009, when peak discharges were about 500 $\mathrm{m^3\,s^{-1}}$ (Figure 4), shear stresses and associated sediment reworking would have been even greater than in 2010, when our calculations suggest that shear stresses produced at least partial mobility of the bed. This highlights the influence of bed mobility, scour depth and the sequencing of high-flow events on fine-sediment residence time.

Our observation that, despite a persistence of high fine sediment content, the sediments in the bed have relatively low contaminant concentrations, has implications both in terms of understanding not only substrate mobility but also the persistence of metals-related impacts of the Milltown Dam removal. Following downstream transport and deposition of contaminated sediments in 2008, impacts to benthic ecosystems were uncertain. No data on invertebrate or fish response to sedimentation within the vicinity of our study reach were collected, although anecdotal accounts of poor angling in 2008 were suggestive of impacts (Chaney, 2009). Our findings suggesting short residence time of fine sediments and relatively low metals concentrations in the bed as of 2010 suggest that, as a result of a series of high flows and associated bed mobility, impacts associated with deposition of contaminated fines in the bed following the removal of Milltown Dam may have been limited in duration. More broadly, this suggests that fine sediment impacts may be lower in magnitude and duration in more mobile, dynamic rivers and/or during wetter periods with more frequent high flows.

Our study also provides insight into sediment sampling methods and their viability in larger rivers. Our field site was larger in terms of flow and associated channel dimensions than others in which similar methods have been applied (e.g. Lisle, 1989; Schindler Wildhaber *et al.*, 2012). Flow conditions limited wading access to parts of the channel, and coarse bed materials created challenges. Even with a modified McNeil sampler to accommodate the larger average grain sizes, our bulk samples were still not large enough to avoid sample bias (Church *et al.*, 1987). Many of our attempts to collect freeze cores were unsuccessful as a result of attachment of large grains to sampler poles and breakage of poles while pounding them into the bed. Despite these difficulties, our use of a cataraft allowed deployment of a heavy, liquid nitrogen and winch system in multiple portions of our field site and successful extraction of 13 samples (Supporting information). By combining bulk sampling, freeze cores and infiltration bags with geochemical fingerprinting, we were able to develop insights specific to post-dam removal sediment infiltration and general to the dynamics of FSI in field settings.

CONCLUSIONS

We combined previous FSI work into a conceptual model, which we tested using a combination of field methods and sediment fingerprinting. The formation of a seal, which

DOI: 10.1002/rra

has previously been observed in field and flume settings, was not found in our freeze cores. Freeze cores, tracer gravels, infiltration bags and metals data also suggest that a mobile bed in our field site limits the residence time of infiltrated fine sediments. Metals concentrations within the substrate were low relative to earlier observations of metals in suspended sediment and in lateral deposition settings, suggesting that successive high flows have limited the duration of FSI-related impacts resulting from a dam-removal sediment pulse.

ACKNOWLEDGEMENTS

Funding was provided by the NSF (EAR-0809082, EAR-0922296, EPS-0701906), Montana Water Center, Geologic Society of America, and the Rocky Mountain Section of SEPM. We thank Johnnie Moore and Heiko Langner for their assistance with the metals analysis and interpretation; Molly Staats, Katy Garcia, Ivan Orsic and Ben Gardner for the assistance with field sampling and laboratory analysis of metals in bed sediment; Aleksandra Wyzgda for the freeze core equipment and associated guidance; and Stanford Gibson for the review comments that greatly improved the manuscript.

SUPPORTING INFORMATION

Supporting information online shows a video of the freeze core sampling methods employed here.

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