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SPATIAL VARIABILITY OF POOL-TAIL FINES IN MOUNTAIN GRAVEL-BED STREAM AFFECTS GRID-COUNT RESULTS[1]

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ABSTRACT: Fine sediment (<2 and <6 mm) particles underlying a 49-intersection grid placed on a streambed at 25, 50, and 75% of the wetted pool-tail width are commonly counted to assess the status and trend of aquatic ecosystems or to monitor changes in the supply of fines in mountain gravel-bed streams. However, results vary even when crews perform nearly identical procedures. This study hypothesized that spatial variability of pool-tail fines affects grid-count results and that a sampling scheme can be optimized for precision and accuracy. Grid counts taken at seven evenly spaced locations across the wetted width of 10 pool tails in a pool-riffle study stream indicated a bankward fining trend with secondary peaks of fines within the stream center. Sampling locations close to the waterlines harbored more than twice as many fines as central locations. Most of the five grid-count schemes derived from the seven sampled locations produced significantly different results. Compared with sampling at all seven locations, schemes that focus near waterlines overpredicted fines, while those that focus on the center underpredicted them. Variability of fines among pool tails was the highest within a broad band along the waterlines; hence, focusing sampling there yielded the most variable results. The scheme sampling at 25, 50, and 75% of the wetted width had the lowest precision and moderate accuracy. Accuracy and precision of grid-count results can be greatly improved by sampling at seven even-spaced locations across the pool tail.

(KEY TERMS: streambed sediment; surface fines; bedmaterial sampling; fluvial processes; channel morphology; geomorphology; rivers/streams; monitoring; environmental sampling; watershed management.)

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INTRODUCTION

Effectiveness monitoring evaluates the response of measurable stream parameters to changes in watershed management practices. Such monitoring may extend over large regional scales and is carried out by many state and federal agencies (Whitacre *et al.*, 2007; Roper *et al.*, 2010) including the Forest Service's PACFISH INFISH Biological Opinion (PIBO) (Henderson *et al.*, 2005; Heitke *et al.*, 2007, 2009, 2010, unpublished reports) as well as the Aquatic and Riparian Effectiveness Monitoring Program (AREMP, 2007, 2009, 2010). Their field crews typically perform a variety of stream measurements at one or two sites a day using protocols tailored to

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rapid field assessment. One goal in large-scale, multiagency effectiveness monitoring is to quantify change in the amount of fine streambed sediment <2 and <6 mm in "integrator reaches." Those reaches are typically mountain gravel-bed streams that are wadeable at low flow, 1-15 m wide, <0.03 m/m steep, and located at the downstream end of a watershed most of which is located on federal land. Integrator reaches are to represent a response reach (Montgomery and MacDonald, 2002) that is located in an unconstrained valley bottom, and most likely exhibits a pool-riffle or plane-bed morphology (Henderson *et al.*, 2004, 2005; Kershner *et al.*, 2004a,b). Grid counts, in which a physical grid is placed at various locations on the bed and the intersections overlaying fine particles are counted, were developed in the early 1990s (Kramer *et al.*, 1991, unpublished reports) and have undergone continual changes (Bauer and Burton, 1993; Overton *et al.*, 1997; Roper *et al.*, 2002; Sylte, 2002; Gallo *et al.*, 2005; Montana DEQ, 2009). Grid counts are a relatively fast field technique that requires about a minute per grid. They were adopted as a common technique for effectiveness monitoring of streambed fines in pool-tail areas about 10 years ago. Obvious advantages of grid counts on (coarse) gravel beds is the focus on fine particles and the visual identification of fines under grid intersections with a plexiglass viewer as opposed to particle selection by feel as done in most pebble count procedures. Cobble embeddedness has been largely dismissed as a suitable practice for monitoring fines (Sylte, 2002; Sylte and Fischenich, 2002; Sennatt *et al.*, 2006, 2008; Potyondy and Sylte, 2008), and volumetric bulk sampling is prohibitively laborious in coarse gravel beds where multiple samples each weighing hundreds of kilograms are required for representative sampling (Church *et al.*, 1987; Bunte and Abt, 2001a).

Grid counts were initially performed on a variety of different morphological units ranging from riffles, runs, and pool tails (Kramer *et al.*, 1991, unpublished reports) to the scour pool-tail crest area and low-gradient riffles (Overton *et al.*, 1997). Effectiveness monitoring by PIBO and AREMP confined the sampled area to the wetted pool-tail area in scour and plunge pools a short distance (10% of the pool length) upstream from the riffle crest (Roper *et al.*, 2002; Archer *et al.*, 2004; Henderson *et al.*, 2004). Selection of this particular sampling area reflects not only the tendency of fine sediment to become trapped there during moderate and low flows (e.g., Lisle and Hilton, 1992, 1999), but also the area just upstream of the pool-tail crest serves as spawning habitat for salmonid fish. Flow passing through the riffle can bring with it fine sediment that then infiltrates into spawning redds. Clogging interstitial pores with fine sediment diminishes oxygenation and waste removal from the redd and may prevent hatchling fish from emerging to the surface (e.g., Chapman, 1988; Lisle, 1989; Bjornn and Reiser, 1991). Not only the location but also the size of streambed fines to be monitored with grid counts changed over time (Bunte and Swingle, 2010) from initially those <6.35 mm (i.e., 0.25 inch) (e.g., Kramer *et al.*, 1991, unpublished reports), to those <6 mm (e.g., Bauer and Burton, 1993), then those <2 mm (e.g., Frazier *et al.*, 2005), and finally both <6 and <2 mm (see above reports by PIBO and AREMP).

The PIBO and AREMP programs worked to further develop and standardize grid-count protocols. The programs used grids with 7×7 (=49) intersections spaced 2 inches (5 cm) apart plus a 50th point in a corner of the sampling frame (Archer *et al.*, 2004; Henderson *et al.*, 2004). The practice of tossing a grid to the center, left, and right portion of the wetted pool-tail width in four (Henderson *et al.*, 2004) or 5-20 scour pools (Frazier *et al.*, 2005) appears to have been abandoned. Beginning in 2003 (as reported by Fausti *et al.*, 2004; Archer *et al.*, 2006, 2008, unpublished reports), the PIBO and AREMP monitoring groups placed (rather than tossed) the grid along a transect located at a distance 10% of the pool length, but no more than 1 m, upstream from the riffle crest at 25, 50, and 75% of the wetted pool-tail width in 10 consecutive scour or plunge pools per reach. The portion of the pool-tail target area not sampled also became more strictly defined. Henderson *et al.* (2004) excluded zones of stagnant flow and patches covered by vegetation. Fausti *et al.* (2004) excluded areas covered by large woody debris, whereas the PIBO and AREMP protocols excluded boulders >512 mm. The PIBO and AREMP protocols nevertheless continue to differ in the width of the sampled pools: AREMP (working in the Pacific Northwest) samples only full pools that extend over >90% of the wetted width (w_{wet}), whereas PIBO (working in the upper Columbia basin) includes partial pools that extend over at least 50% w_{wet}. Despite continued efforts toward standardization (Henderson *et al.*, 2005; AREMP 2007, 2009, 2010; Heitke *et al.*, 2007, 2009, 2010, unpublished reports; Whitacre *et al.*, 2007), grid-count results obtained in a multiagency comparative field study conducted over a wide variety of streams differed notably (Roper *et al.*, 2010). Consistency among the two to six field crews sent from the seven monitoring groups was low (coefficients of variation were 26-64%), and the mean percent fines <2 mm ranged from 19 to 30% among monitoring groups, much of which Roper *et al.* (2010) attributed to each agency using their own version of the grid-count procedure. Results also differed between the experienced

PIBO and AREMP crews who, except for different cut-off values in the minimum sampled pool width, follow the same protocol. AREMP crews obtained a mean percentage of fines in plane-bed and step-pool streams about twice as high as that of the PIBO crews. To improve accuracy as well as comparability among grid-count results, a reduction in the variability of grid-count outcomes among crews, among protocols, and among pool tails of the reach is desirable.

The standardization of grid-count practices undertaken over the years did not include testing of different sampling schemes that cover different portions of the pool-tail area. This study hypothesized that the spatial distribution of fine sediment within pool-tail areas affects the sampled percentage of fines as well as the variability and accuracy of grid-count results. Spatial trends for fines within pool-tail areas have been indicated in several studies (e.g., Bridge and Jarvis, 1976, 1982; Lisle and Madej, 1992), and several processes are known that can cause fines to be spatially variable within pool-tail areas. At high flows, streambed fines are subject to lateral sorting by secondary currents that move fines toward banks and onto gravel bars (e.g., Bridge and Jarvis, 1976, 1982; Dietrich and Smith, 1984; Thompson, 1986; Dietrich and Whiting, 1989; Anthony and Harvey, 1991; Julien and Anthony, 2002; Thompson and Wohl, 2009). Thus, streambed fines can be expected to be high on the barward side of pool tail areas (i.e., away from the outside bend) (Lisle, 1989). Fines are also deposited in slow-flow areas and recirculating eddies along the banks such as in backwater areas (e.g., small bays in the bankline), in small channels along the bankward side of gravel bars, as well as in the wakes of cobbles, boulders, and large woody debris. As a result of these processes, fines are high along the sides of a stream and occasionally on patches within the w_{wet}. At moderate or low flows, fines may be eroded from bar toes and off riffles and transported along streaks or lobes within the w_{wet}, causing fines to be locally higher in central than in lateral portions of the w_{wet}. The cumulative effects of the various sedimentation processes suggest that pool-tail fines increase toward one or both banks with occasional secondary highs within the central w_{wet}. The location and total amount of fines within the pool-tail area may also change during the low-flow period (Adams and Beschta, 1980; Archer *et al.*, 2004; Roper *et al.*, 2010), not only because the strength and location of secondary flows – and thus the temporary transport paths of fines – may change over a range of low flows, but also because the w_{wet} narrows or expands with stage during the low-flow sampling period. Hence, the timing of sampling can also affect the percent fines sampled within w_{wet}.

Given these likely patterns of spatial variability, the question arises: How do specific pool-tail sampling locations as well as the number of grid placements (i.e., sample size) affect the sampled percent fines? Specifically, this study addressed three questions: (1) What is the spatial variability of fines laterally and longitudinally within pool-tail areas? (2) Do results obtained from grid-count schemes with different lateral coverage demonstrate a systematic difference in the measured percentages of fines as well as in variability and accuracy? and (3) Can precision and accuracy of grid-count results be improved by selecting specific sampling locations within a pool tail or by counting more than the typical three locations per target transect?

METHODS

Study Reach

The 416-m long study reach was located at the North St. Vrain Creek in Wild Basin (Rocky Mountain National Park) near Allenspark in the Colorado Front Range, a morphologically diverse, wood-poor, third-order, coarse gravel-bed stream. The North St. Vrain has a pool-riffle morphology with exposed gravel bars and takes an irregular meandering course through a willow thicket covering fluvio-glacial valley fill. Stream gradient between the top and bottom of the reach is 0.007 m/m; w_{wet} and bankfull width (w_{bkf}) in the reach are 11.2 and 14.1 m, respectively (Figure 1). The

FIGURE 1. Photo of the Lower End of the Study Reach. View is downstream. The right person is standing 1 m upstream from the pool-tail crest at the pool-row cross-section.

North St. Vrain is not only a good example of an "integrator reach" but also sufficiently wide to place multiple grids within a pool tail, and pool-tail crests were developed well enough to be identifiable. The 32-km^2 watershed reaches from 2,534 to 3,990 m in elevation and is largely unimpaired. The upper portion lies above treeline, the lower half is forested. The lithology is mainly schist and granite. Scarcity of instream wood was desirable for this study in order to focus on a typical pattern of spatial distribution of fine sediment in a pool-riffle stream as opposed to the localized scour and deposition that may develop around large woody debris. The North St. Vrain has a snowmelt regime, and sampling took place during early fall low flows that were within 5-10% of bankfull flow.

A 1,125-particle, reach-covering pebble count that collected one surface particle every 0.3 m on 27 transects spanning the w_{bkf} using the Sampling Frame and Template procedure (Bunte *et al.*, 2009) indicated D_{16}, D_{50}, and D_{84} particle sizes of 5, 44, and 85 mm, respectively; 10.2% of the particles were <2 mm, 16.4% <5.7 mm. Submerged bars, riffles, and pools had coarser D_{50} sizes and less fines than the bankfull reach, whereas exposed bars and backwater areas along the banks of the main channel had smaller D_{50} sizes and more fines (Bunte and Swingle, 2010). Ten consecutive scour pools and their pool-tail crests were identified within the reach following the PIBO criteria (Heitke *et al.*, 2007, 2009, 2010, unpublished reports): eight of the pools were partial pools (w_{pool} >50% w_{wet}) and two were full pools (w_{pool} >90% w_{wet}). In some pool tails, the gravel bar adjacent to the pool was a mid-channel bar. The streambed on the far side of mid-channel bars had shallow flow and was typically dominated by backwater. Pool-tail measurements were not taken in those areas. Sampled pools were 11 to 30 m long and maximally 0.44-0.91 m deep; thalweg depths at pool-tail crests were 0.25-0.35 m.

Grid Counts

A 0.6 × 0.6 m (inside diameter) aluminum sampling frame otherwise used for pebble counts (Bunte and Abt, 2001a,b; Bunte *et al.*, 2009; see also Roper *et al.*, 2002) was employed to form a physical grid. Thin elastic, white bands about 1 mm wide were spanned over notches along the frame to form a 7 × 7 grid with 5 cm spacing (Figure 2). This arrangement was considered comparable in application and accuracy to the wire grids used in the PIBO studies. A clear 28 × 36 cm (11 × 14 inch) plexiglass picture frame with a 2.5-cm (1-inch) rim was held on top of the water surface to improve visibility. The number of fine particles <2 and <6 mm under 49 intersections plus a 50th sampling point in one of the frame corners was counted and recorded, and the percent fines was computed for each placed grid. The act of counting the number of fines typically took about a minute per grid. The majority of the field effort was spent identifying and measuring pool dimensions while wading on a slippery bed. To the extent possible, wading activity was carried out moving from downstream to upstream to minimize particle entrainment that would distort results.

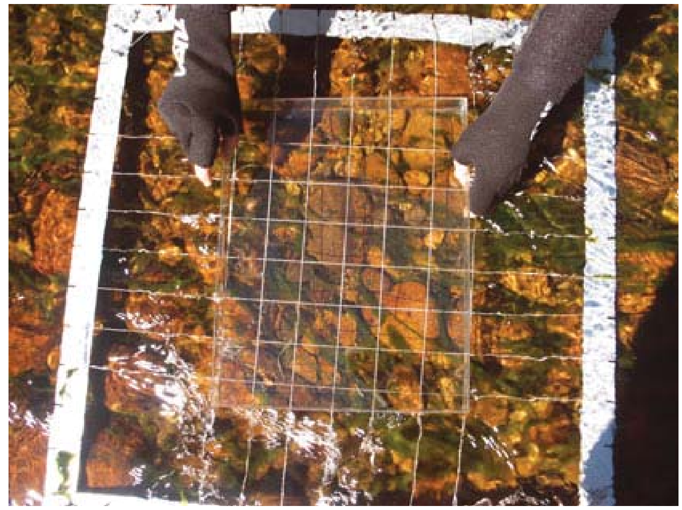

FIGURE 2. Photo of a 0.6 × 0.6 m Sampling Frame with Thin Elastic Bands That Form Intersection with 0.05 m Spacing Was Used as a Grid in This Study. A plexiglass viewer improved the visibility of the bed.

Sampling Schemes. Grids were placed along an imaginary line parallel to and 1 m upstream of the pool-tail crest (all study pools exceeded 10 m in length) at visually estimated locations of 12.5, 25, 37.5, 50, 62.5, 75, and 87.5% w_{wet} (Figure 3). Five sampling schemes each symmetrical about the wetted stream center line were devised from the seven grid locations (Table 1, Figure 4). The three locations of the *Midline 3* scheme focus on the central w_{wet} and exclude lateral stream portions. The three locations of the *Center 3* scheme represent the PIBO protocol. With two additional grids placed at 37.5 and 62.5% w_{wet}, the *Central 5* scheme increased the number of grids without sampling significantly different pool portions compared with the Center 3 scheme. The seven locations of the *All 7* scheme evenly cover much of the w_{wet}. The three locations of the *Mid+-sides* scheme focus on the stream center and banks and mimic aimed grid tosses in which the lateral grids land close to 12.5 and 87.5% w_{wet} (Henderson *et al.*, 2004; Frazier *et al.*, 2005, their Fig. 4). The percent fines were computed for each grid-count

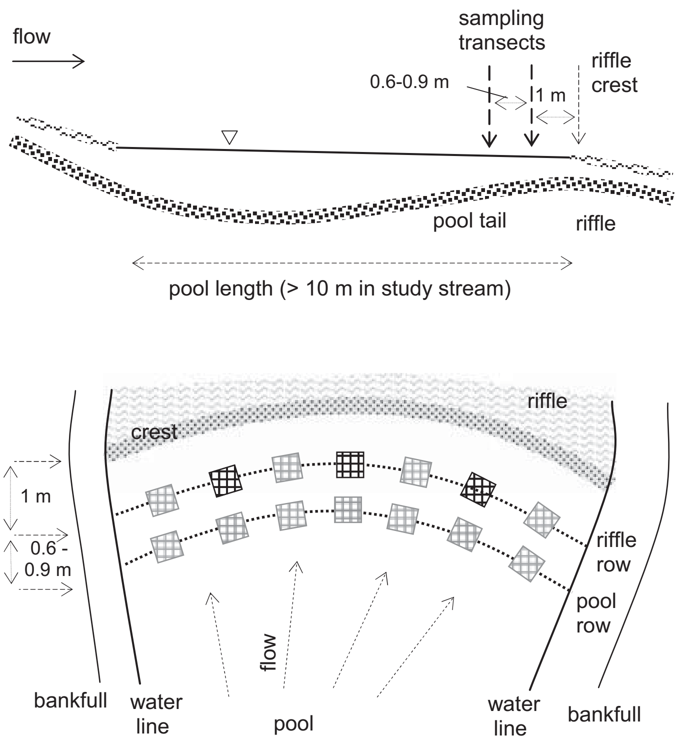

FIGURE 3. Sketch Drawings Showing Longitudinal Profile (top) and Plan View (bottom) of Sampling Locations. Grid signatures indicate grid-count locations (black grids = Center 3 scheme).

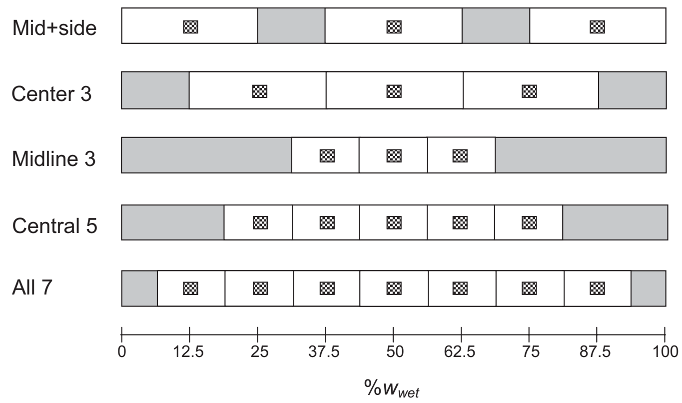

FIGURE 4. Grid-Count Locations (black squares) and Maximum % w_{wet} Represented by Each Grid Location (white areas) Under the Premise That Each Grid Location Lies in the Center of a Width Increment. Portions of w_{wet} unrepresented by a grid-count scheme are shown as gray areas.

scheme as the average of the percent fines counted at the respective sampling locations.

Riffle Rows Vs. Pool Rows

The exact location of the pool-tail crest can be difficult to determine when pool tails take the form of a short run before transitioning into the riffle (Archer *et al.*, 2004). Multiple operators may therefore select pool-tail target transects that differ by up to a meter in the upstream–downstream direction. In this study, only one observer identified and quantified pool dimensions, thus avoiding this specific aspect of multiple observer variability. The potential effects of the upstream–downstream variability on sampled pool fines was assessed by sampling a second transect with seven grids (termed *pool row* as it faces the pool) 0.6-0.9 m upstream from the first transect (termed *riffle row*), such that a total of 140 grid locations was sampled in the 10 pool-tail areas.

Two Operators Sampling Identical Locations. To evaluate operator error in visually identifying whether a particle is larger or smaller than 2 or 6 mm and in accurately counting their occurrences (viewing and counting error), two operators counted fines <2 and <6 mm at each grid location, typically simultaneously but unavoidably from slightly different viewing angles. The slightly different bed area thus sampled possibly contributed to operator variability. Total operator variability that would include independent identification of pool-tail crests and grid placements by each operator was not evaluated. Other than for the evaluation of operator variability, sampling results were averaged over the two operators.

TABLE 1. Five Sampling Schemes Devised from the Seven Grid Locations.

Scheme Name	Sampling Locations (in % w_{wet})							Number of Grids	Portion of w_{wet} Covered by Grid Locations (%)	Max. % w_{wet} Represented*
Midline 3			37.5	50	62.5			3	Center 25	37.5
Center 3		25		50		75		3	Center 50	75
Central 5		25	37.5	50	62.5	75		5	Center 50	62.5
All 7	12.5	25	37.5	50	62.5	75	87.5	7	Center 75	87.5
Mid+sides	12.5			50			87.5	3	Center 75	75

*If each grid location is taken as the center of a width increment that extends halfway toward a neighboring width increment.

Computational Analyses

Statistical Tests. Sampled percentages of fines among operators and among sampling schemes were compared for statistical similarity using a paired t-test and the nonparametric matched-pairs Wilcoxon signed-rank test, referred to as W-test in this study. The latter does not require test data to be normally distributed and is applicable to sample sizes $n < 20$. Test evaluations were based on a 95% confidence level. The coefficient of variation (CV%) was computed as the ratio of sample standard deviation to sample mean multiplied by 100.

RESULTS

Differences Depending on Sampling Location

Bankward Fining Trend Interrupted by Patches of Fines. The grid-count percentages of fines <2 and <6 mm varied among sampling locations. For brevity, explanations of lateral variability are limited to results averaged over the pool-tail riffle and pool rows (Figure 5), but apply similarly to riffle and pool rows individually. Grid-count locations within the center one-third portion of w_{wet} or close to the thalweg (which was not confined to the central portions of w_{wet}) typically showed the least amount of fines. The highest concentration of fines was found where pool tails bordered exposed gravel bar or backwater deposits, as expected from secondary flow patterns. Bars occurred on alternate sides of consecutive pools based on the meandering course of the stream, thus high lateral concentrations of fines typically alternated from side to side as well. In several pool tails, the lateral fining trend was interrupted by local patches with high fines near the thalweg or within the center half of the channel width.

Marginal Pool-Tail Fines Two to Three Times Higher Than Central Pool-Tail Fines. Fines exhibited a lateral fining trend from the stream center toward the waterlines. Pool-tail margins averaged over 12.5 + 87.5% w_{wet} (again riffle and pool rows combined) had more than twice as many fines <2 and <6 mm as the central pool-tail locations averaged over 37.5 and 62.5% w_{wet}; the locations of 25 and 75% w_{wet} had approximately 1.7 times the percentage of fines in pool-tail centers (Table 2), and the fining trend was slightly more developed for fines <2 mm than for fines <6 mm. Marginal pool-tail fines <2 and <6 mm at 12.5 and 87.5% w_{wet} were statistically different (W-test) from those collected at other locations,

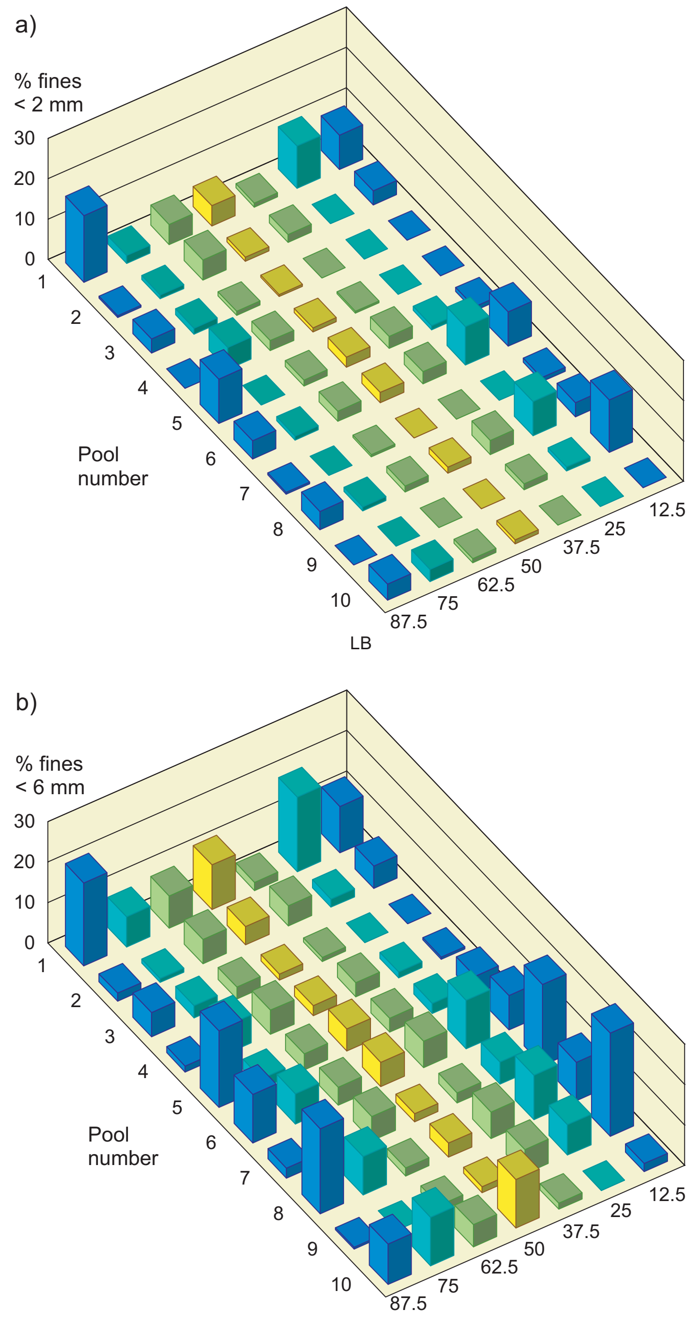

FIGURE 5. Percent Fines <2 mm (a) and <6 mm (b) Sampled Over All Seven Locations at the 10 Pool Tails of the Study Reach, Showing an Increase of Fines Toward the Waterlines. Sampling results are averaged over riffle and pool rows and over the two operators. Dotted lines indicate the thalweg.

whereas differences in the percentages of fines sampled at any of the locations (25, 37.5, 50, 62.5, and 75% w_{wet}) within the central half of pool tails were not statistically significant. These results suggest that inclusion or exclusion of sampling locations close to the waterlines may lead to statistically different percentages of measured fines.

TABLE 2. Percentages of Fines Counted at Various Sampling Locations and Averaged Over All Study Pools, As Well As Variability of Fines (CV%).

Sampling Location (% of w_{wet})	% <2 mm			CV% <2 mm			% <6 mm			CV% <6 mm		
	Riffle Rows	Pool Rows	Mean	Riffle Rows	Pool Rows	Mean	Riffle Rows	Pool Rows	Mean	Riffle Rows	Pool Rows	Mean
12.5	4.1	3.7	3.9	110	150	117	8.8	8.7	8.8	88	109	96
25	3.6	2.5	3.1	147	156	147	7.4	4.7	6.1	112	94	102
37.5	1.4	1.5	1.5	140	90	94	3.4	4.2	3.8	71	73	55
50	1.5	1.5	1.5	90	123	101	5.5	4.5	5.0	114	58	76
62.5	1.9	2.2	2.1	141	113	85	3.9	5.4	4.7	107	59	44
75	1.5	1.5	1.5	114	134	113	5.4	4.7	5.1	84	95	83
87.5	4.7	4.3	4.5	133	117	119	9.3	9.7	9.5	87	93	87
Mean												
12.5 + 87.5	4.4	4.0	4.2	99	92	90	9.1	9.2	9.1	58	63	58
25 + 75	2.6	2.0	2.3	110	101	102	6.4	4.7	5.6	86	68	73
37.5 + 62.5	1.7	1.9	1.8	82	82	68	3.7	4.8	4.2	44	40	25
All seven locations	2.7	2.5	2.6	90	69	77	6.2	6.0	6.1	56	41	52

Variability of Fines Among Pools. An analysis of how fines varied over the pools of the reach when sampled at different lateral locations sets the stage for the degree of variability obtained from various sampling schemes. If, for example, fines close to the water's edge varied more among the pools of the reach than those sampled near the pool-tail center, then sampling schemes focusing on the water's edge would experience a higher variability over the reach than sampling schemes focusing on the central portions of the pool-tail width.

As expected, fines <2 and <6 mm sampled near the pool-tail center and averaged over 37.5 + 62.5% w_{wet} exhibited the lowest CV over the reach for riffle and pool rows combined as well as individually for each row (Table 2). Fines averaged over 12.5 + 87.5% w_{wet} varied moderately, whereas those averaged over 25 + 75% w_{wet} had the highest CV. Fines <2 mm were about twice as variable over the reach than fines <6 mm, and sampling on riffle rows resulted in a slightly lower CV than sampling on pool rows or sampling on pool and riffle rows combined. The high variability of fines <2 mm at 25 or 75% w_{wet} may be caused by secondary flows that accumulate sand on submerged bar toes in some of the pool tails during low flows. The pattern of variability observed in the study stream suggests that a grid-count scheme sampling fines <2 mm at 25 and 75% w_{wet} on riffle rows in pool-riffle morphologies may see a high variability of sampled fines among pool tails (Table 2). By contrast, low variability can be expected for a grid-count scheme that samples fines <6 mm near the stream center and averaged over riffle and pool rows.

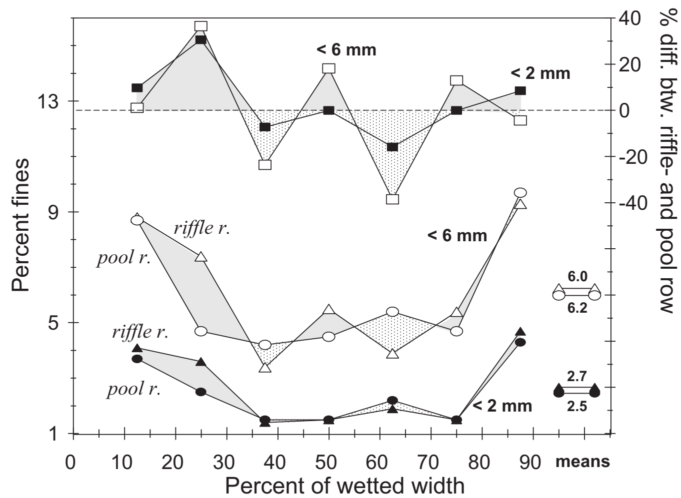

FIGURE 6. Percent Fines <2 and <6 mm Sampled on Riffle and Pool Rows at All Seven Locations Over the w_{wet} and Averaged Over All Study Pools (lower two line pairs). Average % difference in fines between riffle and pool rows at all seven locations (upper line pair) is provided. Gray-shaded areas indicate locations where riffle rows on average have more fines than pool rows, dotted areas where pool rows have more fines than riffle rows.

Longitudinal Differences in Fines: Riffle *Vs.* Pool Rows. Averaged over all study pools and sampling locations, riffle rows yielded slightly more fines (4-8%) than pool rows (Table 2), which is statistically insignificant and could be neglected if it was not for an odd zig-zag pattern that appeared in the difference between riffle- and pool-row fines (Figure 6). At the sampling locations of 25, 50, and 75% w_{wet}, riffle rows had about 20% more fines <6 mm than pool rows, whereas, at the locations 37.5 and 62.5% w_{wet}, pool rows had about 30% more fines. The circular movement of fines in pools described by Thompson and Wohl (2009) can explain part of the observed zig-zag pattern: fines travel toward the pool tail along the stream center or thalweg, but the path

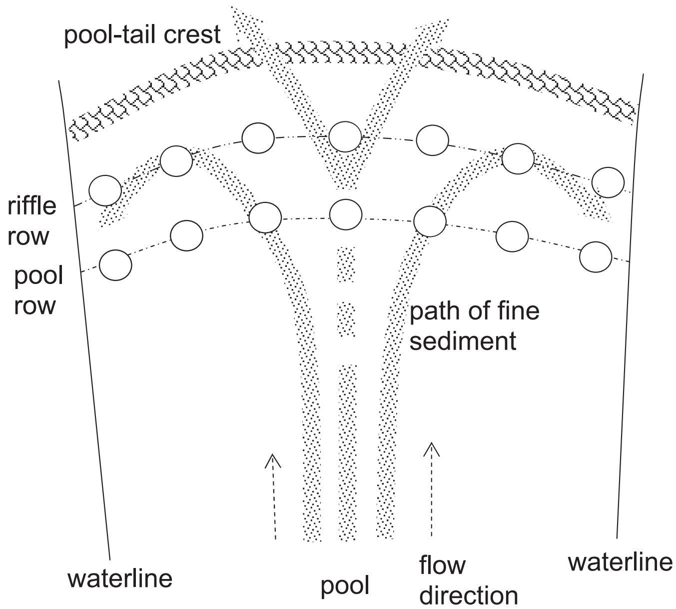

FIGURE 7. Schematic Sketch Drawing of the Fine Sediment Travel Path in a Pool Tail (after Thompson and Wohl, 2009). Circles show the seven sampling locations on riffle and on pool rows.

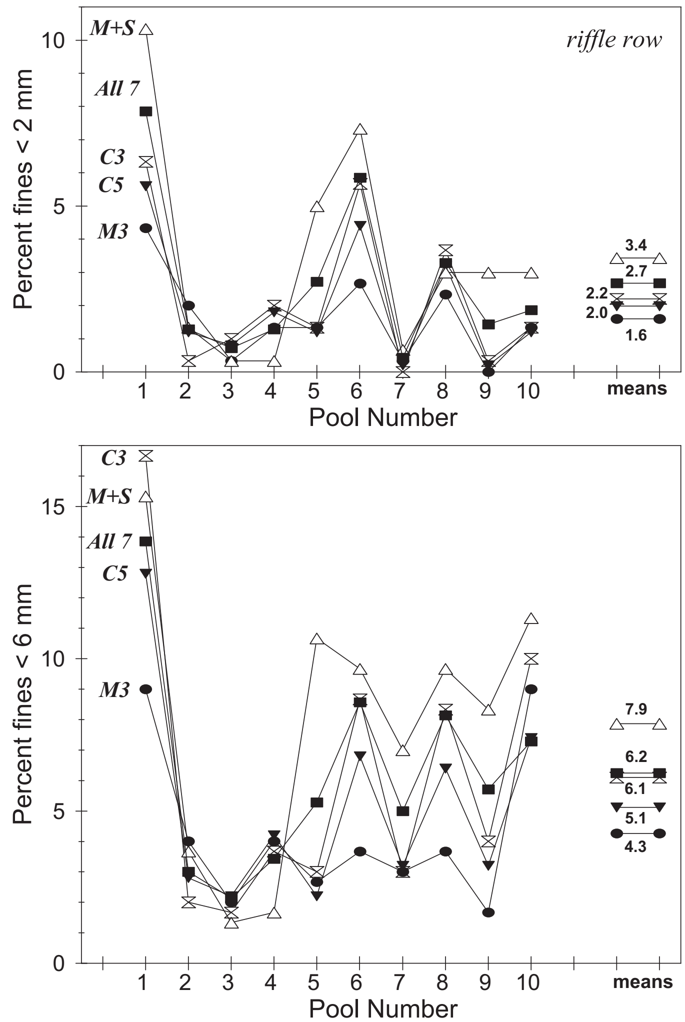

FIGURE 8. Percent Fines <2 and <6 mm and Mean Percent Fines Obtained from Five Grid-Count Schemes on Riffle Rows at All 10 Pool-Tail Areas. Data are averaged over both operators. The Midline 3, Central 5, and All 7 sampling schemes in which grid locations progressively expand more bankward have black symbols. Schemes that focus on center and lateral locations have white symbols.

splits turning to either side before reaching the pool-tail crest (Figure 7).

The notably higher amounts of fines at 25, 50, and 75% w_{wet} on riffle rows suggests that a grid-count scheme sampling at just these locations on riffle rows has noticeably more fines than if it sampled on pool rows. By contrast, a scheme that focuses at 37.5 and 62.5% w_{wet} on pool rows will have more fines than if it sampled on riffle rows. Thus, if differences exist in the bankward fining trend between riffle and pool rows, then sampling on riffle or pool rows may yield different results, especially if sampling schemes are used that focus on a few lateral locations instead of covering the stream width more intensively.

Differences Among Grid-Count Sampling Schemes

Percentage of Fines Increases with Extent of Lateral Coverage. Each of the five grid-count schemes yielded a different percent fines over the study pool tails (Figure 8). Following the bankward fining trend, the percentage of fines steadily increased as progressively wider sections of w_{wet} were sampled by individual schemes. The analysis presented here focuses on riffle rows, but trends were similar for pool rows as well (Table 3). Compared with the center-focused Midline 3 scheme, the more widely spread Central 5 scheme obtained 24% more fines <2 mm, whereas the width-spanning All 7 scheme obtained another 35% more than Central 5. Similarly, Central 5 indicated 20% more fines <6 mm than Midline 3, and the All 7 scheme 22% more than Central 5. Results from the All 7 scheme were statistically different from the Midline 3 and Central 5 schemes. The Mid+sides scheme, by contrast, with one sampling point in the stream center and two near the waterlines, indicated 28.5% more fines <2 mm than the All 7 scheme, as well as a statistically significant 26% more fines <6 mm. The Center 3 scheme that excludes the locations 37.5 and 62.5% w_{wet} where fines were relatively low but that extends over the same width as Central 5 yielded 21% less fines <2 mm compared with the All 7 scheme and 2% less fines <6 mm. Hence, the percent fines obtained by the Center 3 scheme were closest to and statistically

TABLE 3. Percent Fines <2 and <6 mm on Riffle and Pool Rows Averaged Over the 10 Study Pools and Coefficients of Variation Obtained from the Five Grid-Count Schemes.

Grid-Count Scheme	Mean Percent Fines in Study Reach										Coefficient of Variation (%)					
	Both Rows		Riffle Rows				Pool Rows				Both Rows		Riffle Rows		Pool Rows	
	<2 mm	<6 mm	<2 mm	% diff.	<6 mm	% diff.	<2 mm	% diff.	<6 mm	% diff.	<2 mm	<6 mm	<2 mm	<6 mm	<2 mm	<6 mm
Midline 3	1.7*	4.5*	1.6*	24	4.3†	20	1.7†	6	4.7†	0	71	35	81	61	76	35
Central 5	1.9*	4.9*	2.0*	35	5.1*	22	1.8†	34	4.7†	27	79	48	92	65	70	40
All 7	**2.6**	**6.1**	**2.7**	21	**6.2**	2	**2.5**	34	**6.0**	29	**77**	**46**	**90**	**55**	**69**	**41**
Center 3	2.0†	5.4	2.2	56	6.1	29	1.8	73	4.6†	65	97	67	103	78	94	57
Mid+sides	3.3†	7.8†	3.4		7.9*		3.2		7.6*		89	52	96	57	92	53
Average											83	50	92	63	80	45

Notes: The percent difference (% diff.) refers to fines in sampling schemes listed below each other (e.g., 24 = % difference in fines <2 mm between the Midline 3 and the Central 5 scheme). Compared with results from the All 7 scheme (bold print) and based on the *W*-test, the percent fines from an indicated sampling scheme is either significantly different at $p < 0.05$ (*), borderline different at $p < 0.1$ (†), or not statistically different (no superscript symbol).

not different from the All 7 results sampling at seven locations.

Wide Grid Tosses Yield More Fines Than Even-Spaced Grid Placements. As both the Mid+sides and the Center 3 scheme are relatively similar and are widely used, it is interesting to compare their results. Mid+sides mimics aimed grid tosses in which the two marginal grids are located near the waterline at 12.5 and 87.5% w_{wet}, whereas Center 3 places the two marginal grids slightly more inward at 25 and 75% w_{wet}. Mid+sides yielded a statistically significant 56% more fines <2 mm as well as 29% more fines <6 mm than Center 3 (Figure 8). Hence, a shift of the two marginal grids from 25 and 75% w_{wet} closer toward the waterlines resulted in a significantly higher percentage of sampled fines.

Only Center 3 Scheme Had Significantly More Fines on Riffle Than on Pool Rows. Pool tails that transition into a run before reaching the riffle crest can make it difficult to identify the target sampling transect ≤1 m upstream from the pool-tail crest (=riffle row). As a result, different crews may place transects differently by up to a meter in the upstream–downstream direction (Archer *et al.*, 2004). Although the effects may be insignificant in some cases, selecting slightly different transects may notably alter the sampled percent fines if a grid-count scheme is sensitive with respect to longitudinal grid placement. The only scheme that sampled about 20% more fines <2 and <6 mm on riffle than on pool rows (statistically significant, both *t*-test and *W*-test) was Center 3 (Table 3) because it sampled at 25, 50, and 75% w_{wet} where fines were substantially higher on riffle than on pool rows (Figure 6). The other grid-count schemes were less affected by riffle- and pool-row differences because they either did not sample at 25 and 75% w_{wet} or they integrated over more than three sampling locations.

Variability Over Study Pools Differs Among Grid-Count Schemes. The degrees of variability in the measured percentage of fines over the 10 study pools directly affects the statistical rigor of the sampling results. If, for example, the variability of fines over the study pools for one grid-count scheme was higher by a factor of 1.41 ($2^{0.5}$) than that for another scheme, then the first sampling schemes either requires a sample size that is larger by a factor of 2 for a specified statistical confidence or it has twice the error for the preset sample size.

The variability in fines differed among the five grid-count schemes. Focusing again on the example of riffle rows, the Midline 3 scheme, sampling close to the stream center had the lowest CVs in the percent fines <2 and <6 mm (81 and 61%, respectively) (Table 3), followed by All 7 that integrated over all seven locations (CV = 90 and 55%). By contrast, Mid+sides (CV = 96 and 57%) that typically indicated the highest and Center 3 (CV = 103 and 78%) that typically indicated the lowest percent fines at all pool tails (Figure 8) produced the most variable results. Hence, compared with All 7, the Center 3 scheme had an error 1.1 times larger for fines <2 mm and 1.4 times larger for fines <6 mm. Expressed in terms of sample size, Center 3 requires 1.3 times more samples for fines <2 mm to reach the same error (or statistical confidence) as the All 7 scheme, and 2 times more samples for fines <6 mm.

Several alternatives may be considered in an effort to decrease variability in grid-count results. Extending the sampled reach over more than 10 pool tails would, however, not improve the precision of counted fines. Assuming that the same set of 10 study pools had been encountered in succession over reaches twice and five times as long, that is, computing the CV over 20 and 50 pool tails, changed the CV insignificantly. In a real stream situation, pool properties likely change over long reaches, thus sampling a longer reach would increase, and not decrease, the CV%. A slight decrease in variability might be achieved from sampling pool rows rather than riffle rows (=current target line for grid counts in many protocols), because CVs for riffle-row fines averaged over all sampling schemes were 15% higher for fines <2 mm and 40% higher for fines <6 mm than CVs on pool rows (Table 3). Combining sampling results from riffle and pool rows also does not reduce variability over the reach because the CVs for fines averaged over both rows were slightly higher than those obtained on pool rows alone. A more effective step toward reducing variability of grid-count results was to employ the Midline 3 or the All 7 schemes that produced the least variable results among study pools. However, Midline 3 does not represent fine-rich areas near the pool-tail banks and thus strongly underpredicted the percent of pool-tail fines. That leaves the All 7 scheme as the only alternative to reduce variability, though at the cost of a higher work effort.

Operator Variability in Identifying and Counting Fines. The two operators in this study produced similar trends in their counted percent fines over the 10 pools, but Operator 2 tended to count slightly more fines <2 and <6 mm where fines were plentiful, whereas Operator 1 counted more fines <6 mm in areas with generally fewer fines. Thus, the magnitude of the difference between operators depended on the amount of fines on the bed. On grids with <3% fines, operator results differed by as much as 200% (a factor of 2), but only by about 20% on grids with 27% fines <2 mm (the highest percentage fines). By contrast, absolute differences between operators increased as higher percentages of fines were encountered per grid location because a higher presence of fines on the bed increases the chance for operator error in correctly identifying and counting fine particles.

As operator variability increased with the amount of fines encountered on the bed, sampling schemes that included fine-rich bankward locations at 12.5 and 87.5% w_{wet} had the highest operator variability. Again, focusing on riffle rows, operator differences (Op. 2 and Op.1) in counted percentages of fines <2 mm increased from 0 under the Midline 3 scheme to 29% under the Mid+sides scheme. For fines <6 mm, operator differences ranged from −9% for the Midline 3 scheme to 12% for Mid+sides (Figure 9). Similar results were observed for pool-row fines. Although the general trend of higher absolute errors

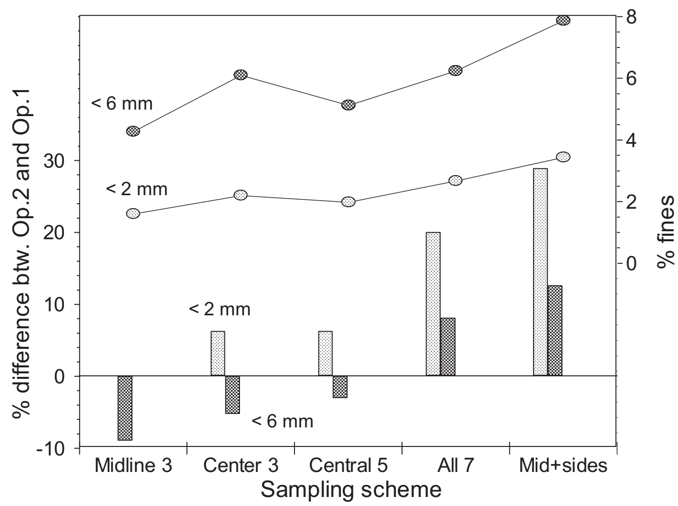

FIGURE 9. Percent Difference in Percent Fines <2 and <6 mm Counted by the Two Operators on Riffle Rows (bars) for Each Sampling Scheme and Increase of Operator Differences with the Counted Percent Fines (both operators combined; data connected by dashed lines).

but lower percentage errors for locations richer in fines may be general, specific errors quantified in this study may represent but one example of operator variability.

Differences in Accuracy Among Grid-Count Schemes. Within the bounds of 12.5 to 87.5% w_{wet}, sampling results from the All 7 scheme with its evenly and tightly spaced sampling locations were taken as the best estimate of the true result. The ratio q (observed/estimated true result) (again focusing on riffle rows) was lowest for the Midline 3 scheme (q = 0.68 and 0.76), somewhat higher for the Central 5 scheme (q = 0.76 and 0.83), and closest to the estimated true results (All 7) for the Center 3 scheme (q = 0.75 and 0.90) (Figure 10); these three schemes underestimated results from the All 7 scheme by 10-30%. By contrast, the Mid+sides scheme (q = 1.24 and 1.22) overpredicted the estimated true results by more than 20%. If fines within 0 to 100% w_{wet} were of interest, the All 7 scheme likely remains the most accurate scheme if waterline fines were similar to those sampled at 12.5 and 87.5% w_{wet}. However, under a strong bankward fining trend with more fines at 0 and 100% than at 12.5 and 87.5% w_{wet}, the Mid+sides scheme with its near-waterline grid locations likely yields results more accurate than the All 7 scheme.

Sampling Scheme Evaluation

Each of the five grid-count schemes had strengths and weaknesses with respect to broadness and

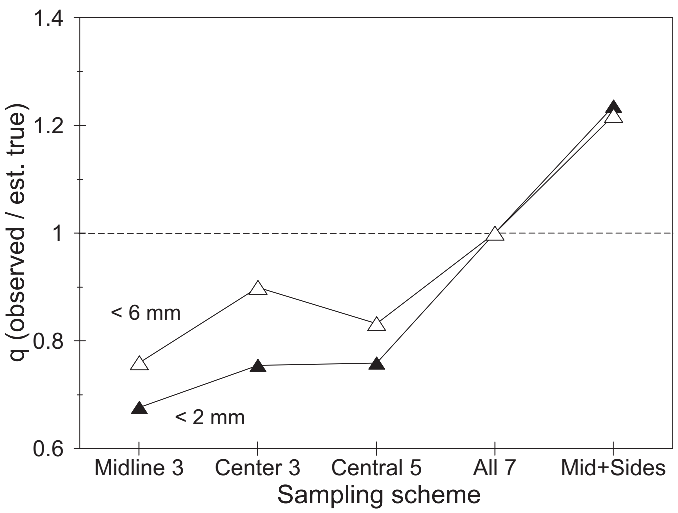

FIGURE 10. Ratios q of Observed Grid-Count Results to Estimated True Results for Fines <2 and <6 mm Counted on Riffle Rows Using the Five Sampling Schemes.

tightness of lateral coverage, work effort, susceptibility to operator variability, difference between riffle and pool rows, variability among the pools of the reach, and sampling accuracy. The All 7 scheme not only had the highest work effort but also covered the transect most broadly and tightly, that is, most representatively (Table 1). All 7 had less than average variability in its percent fines sampled on riffle rows among the pools of the reach (Table 3), but was prone to operator variability. By definition, All 7 was the most accurate sampling scheme within the bounds of 12.5 to 87.5% w_{wet}. Taken together, All 7 was rated the most satisfactory grid-count scheme.

The Central 5 scheme not only had the second best lateral coverage but also the second highest work effort; compared with the other schemes, variability over the reach was average, proneness to operator variability was moderate, and accuracy average, that is, the Central 5 scheme was "average."

Among the three low work-effort schemes, Midline 3 covered the transects incompletely and left much of the stream width unsampled. Midline 3 excelled in its low variability, but had the lowest accuracy. Midline 3 would be the scheme of choice if fines only within a narrow band in the stream center were of interest.

Center 3 is the scheme currently used for large-scale monitoring by various agencies. Broadness and tightness of lateral coverage are unremarkable. Weak points are that Center 3 had the highest variability among pools within the reach of all sampling schemes, and Center 3 was the only scheme showing a notable difference in counted fines between riffle and pool rows. Thus, results from the Center 3 scheme would be most likely affected by operator error with respect to identifying the pool-tail crest and the target sampling transect ≤1 m upstream (Archer *et al.*, 2004). Strong points of Center 3 were a relatively low proneness to operator difference, and the second best accuracy after All 7 when waterline fines were ignored.

The Mid+sides scheme mimics grid tosses to the stream center and the two sides. Its widely spaced grid locations cover a transect broadly but not tightly. Weak points of Mid+sides were susceptibility to operator variability and higher than average variability among pools, but Mid+sides had the least differences between riffle- and pool-row fines. Within the bounds of 12.5 to 87.5% w_{wet}, Mid+sides oversampled and had a relatively low accuracy. However, if one assumed that due to a strong bankward fining trend the true percent fines within 0 to 100% w_{wet} was notably higher than within 12.5 to 87.5%, then Mid+sides would likely produce more accurate results than the All 7 scheme.

SUMMARY AND DISCUSSION

This study demonstrated that pool-tail fines exhibit spatial trends that affect sampling results obtained from five different grid-count schemes:

- *Bankward fining trend*: Marginal pool-tail locations (symmetrically averaged over both sides of the stream) harbored more than twice as many fines (statistically significant) as central pool-tail locations.
- *Difference between grid-count schemes*: Due to bankward fining, the highest % fines was obtained from the scheme that extends furthest toward banks (Mid+sides).
- *Longitudinal differences in the amounts of fines*: Differences in fines sampled on riffle and pool rows were insignificant for all but the Center 3 scheme but can become an issue in streams where the riffle crest is difficult to identify.
- *Variability differed among sampling schemes*: Because variability over the reach was highest at the locations 25 and 75% w_{wet}, Midline 3, focusing on the stream center, and All 7, integrating over many locations, were the most precise, whereas Center 3 and Mid+sides the least precise schemes.
- *Operator variability with respect to identifying, counting, and recording fines*: Operator differences were highest where fines were either plentiful or scarce and became significant for the All 7

and Mid+sides schemes that included the fine-rich locations at 12.5 and 87.5% w_{wet}.

- *Sampling scheme accuracy*: Within the bounds of 12.5 to 87.5% w_{wet}, the even and tight coverage of the All 7 scheme yielded the most accurate results; Center 3, Central 5, and Midline 3 underestimated fines by 10-30%, and Mid+sides overestimated by 20%.
- *Evaluation of all schemes: All 7 overall best*: Sampling schemes exhibited strengths and weaknesses in terms of work effort, broadness and tightness of lateral coverage, variability of sampled fines over the reach, between operators and between riffle and pool rows, as well as accuracy. The All 7 scheme combined good lateral coverage, high accuracy within the bounds of 12.5 to 87.5% w_{wet}, and low variability over the reach; susceptibility to operator variability and high work effort were its weak points. Central 5 obtained moderate results in all categories and was without pronounced strengths or weaknesses. Of the three low work-effort schemes, the strength of Center 3 was low operator variability, and accuracy ranked second behind All 7 when waterline fines were ignored. But of all schemes, Center 3 exhibited the largest variability among study pools as well as between riffle and pool rows. Strong points of the Midline 3 scheme were low variability in sampled fines among pools of the reach and relatively low operator difference. Definite weak points were an unrepresentative lateral coverage and a very low accuracy. Strengths of the Mid+sides scheme were broadness of lateral coverage and low difference between riffle- and pool-row fines. Weaknesses were the patchy lateral coverage, proneness to operator variability, and high variability of fines over the reach. Mid+sides overpredicted fines when waterline fines were ignored, but would likely produce the most accurate results if fines at the waterline were high and their evaluation were part of the study.

Applicability of Study Results to Various Stream Types

This study evaluated spatial variability of fines in pool-tail areas in a mountain gravel-bed stream with pool-riffle morphology because that stream served as a good example of an "integrator reach" in large-scale effectiveness monitoring. Hence, the study stream represents the morphology for which grid counts were intended. However, effectiveness monitoring performs grid counts in other stream types as well, provided their pools fulfill the morphological criteria specified by Henderson *et al.* (2004) and AREMP (2007, 2009, 2010). Plane-bed streams feature occasional pool-riffle sequences, most of which are forced either by sharp bends incised in the course of the stream, by rock outcrops, or by large woody debris. Forced pools may be smaller than pools in pool-riffle streams in which case bankward fining is probably less well developed, and the difference among grid-count schemes might be less. Forced pools may also be more pronounced and subject to strong secondary currents that exceed those encountered in a free-formed pool and cause stronger bankward fining trends. Consequently, results would differ more among various grid-count schemes, but the ranking among them established above would likely remain unchanged. Differences among grid-count schemes more pronounced than in the study stream may be expected in pool-riffle streams that feature a higher percentage of fine sediment coupled with a stronger degree of bankward fining.

Step-pool morphologies are unlikely in integrator reaches with gradients <0.03 m/m, and their pools may not fulfill the specified morphological criteria. Those pools may or may not exhibit notable bankward fining, hence study results may or may not apply. Stream size *per se* does not affect results from this study provided the stream is wider than the space needed to place seven grids, that is, about 2.5 m, and a bankward fining trend is present. If the general idea of sampling pool-tail areas was given up and instead grids were placed on transects spaced evenly over a reach, plane-bed streams would likely show less differences among grid-count schemes due to a lesser lateral variability of fines and less fines in general. By contrast, where fines exhibit a high degree of spatial heterogeneity, such as in braided streams with sand-gravelly beds, or alternate bar streams with a mosaic of different sediment patches, results from this study are likely not applicable.

Other Influences on Grid-Count Results

Apart from spatial variability, grid-count results are influenced by other factors that include spacing of grid intersections, the timing of sampling, lateral sampling extent to waterlines and beyond, and differences in pool definition.

Grid Spacing and Size. This study used a 7×7 intersection grid with a 5-cm spacing and a 35-cm outside dimension, similar to what is used by multi-agency large-scale effectiveness monitoring. However, different grid spacing can affect the sampling result. Ideally, grid spacing should approach the largest bedmaterial particle size because a more narrowly spaced grid introduces serial correlation when a large particle occupies numerous grid intersections or when the grid happens to cover a wake deposit of fine particles. If grid intersections that overlay large particles are included in the computation, they underestimate the % fines (McCullough and Green, 2006), whereas a grid that covers a fine-grained wake deposit overestimates them. A larger grid spacing would thus be desirable, but the resulting larger grid would make handling and placement more cumbersome. Also, in small streams, a larger grid might limit the number of grids that could be placed next to each other. The PIBO program addressed serial correlation caused by very large particles by leaving intersections covering particles >512 mm or large woody debris uncounted on a 50-point grid (Heitke *et al.*, 2007, 2009, 2010, unpublished reports).

Timing of Sampling. On the background of a bankward fining trend and a protocol that samples within the w_{wet}, the exact timing of field work affects sampling results even if several sedimentation factors are considered constant. Assuming no sediment delivery to the channel after peakflow time, secondary flows still re-entrain and re-deposit fines during low and moderate flows and modify the spatial distribution of fines within pool tails. Consequently, the degree of bankward fining is likely to change within the low-flow period, which could increase or decrease differences in results among sampling schemes. Assuming no change in the bankward fining trend over the seasonal low-flow period during which grid counts are typically performed, the presence of such a trend nevertheless affects the sampled percent fines because the absolute width of w_{wet} likely differs between repeated field visits. Results from the Midline 3 scheme would be least affected, because the absolute locations of 37.5, 50, and 62.5% w_{wet} do not shift much with changes of w_{wet}. However, an expansion or contraction of w_{wet} causes an increase or decrease in results from the Central 3 and Mid+sides schemes because the absolute locations of 25 and 75% w_{wet}, and particularly of 12.5 and 87.5% w_{wet}, may shift notably. The problem of variability in spatial distribution of fines could be best addressed by using the All 7 scheme that covers the sampled cross-section widely and densely. Sampling at 7 (or more) locations over the w_{bkf} would largely eliminate this problem, but might introduce uncertainty associated with identifying the bankfull level (Roper *et al.*, 2008).

Lateral Extent of Grid Counts to Waterlines and Beyond. The most commonly used grid-count scheme (Center 3) covers the central 50% of w_{wet}, and in this study, grid counts were extended to cover the central 75% w_{wet} between 12.5 and 87.5%. Would it be useful if grid counts covered the entire w_{wet} or even w_{bkf}? Arguments can be made for and against a lateral extension of the sampling area. Fines increase laterally from the stream center to w_{bkf} (as shown by detailed pebble counts spanning the w_{bkf} in the study stream). The amount of central fines may be affected by post-flood winnowing, as well as entrainment and re-deposition within and out of pools at flows during which fines are typically not supplied to the stream. By contrast, lateral fines that are transported and deposited near the streambanks during high flows do not move much after high flows. Lateral fines are therefore more likely to serve as indicators of fines supplied from the watershed than central fines that experienced weeks of relocation through the stream system during moderate and low flows. This argues in favor of counting fines near (and beyond) waterlines if the sampling aim is detecting change in the delivery of fine sediment from the watershed. (Studies monitoring change following watershed effects should also quantify fines stored in parts of the streambed other than pool tails, such as typical fine-sediment storage areas at the downstream portions of gravel bars, around large woody debris, and in backwater.) Disadvantages of sampling fines at or beyond waterlines are that bankward fines may be more variable (higher CV) among pools of the reach than fines within the central half of the w_{wet} and thus yield less precise sampling results. The amount of fines sampled near the waterlines is also strongly affected by changes in the w_{wet} during the low-flow period (see above). Sampling at fine-rich bankward locations also increases operator chances for viewing and counting errors, and thus operator variability. Finally, when counting fines for fish-habitat studies, it might be less important to consider fines along the pool-tail margins, arguing that fish tend to prefer pool-tail centers for spawning where the interstitial throughflow rate and thus nutrient supply, waste removal, and oxygenation are higher.

Pool Definitions. Not only the lateral but also the longitudinal location of the sampling transect can affect grid-count results. Our study showed that an upstream shift in the pool-tail transect by less than a meter can cause notable differences in amount and variability of sampled fines. Larger effects may be expected when monitoring groups use different definitions as to what constitutes a pool (see Roper *et al.*, 2010), with the result that some monitoring groups sample entirely different pool tails within a reach than other groups.

All 7 Scheme Would Improve Comparability Among Studies

Center 3 is the grid-count scheme commonly used in effectiveness monitoring. However, this study found Center 3 results to be highly variable among pools as well as between riffle and pool rows. Among the low work-effort sampling schemes, precision can be improved when sampling is limited to the stream center (Midline 3), but this gain comes at the expense of accuracy. Precision and accuracy, and thus the comparability among studies, can both be significantly improved by selecting the All 7 grid-count scheme that integrates with even-spaced locations over the pool-tail width. This gain is at the expense of a higher work effort. The additional time of counting fines on seven instead of three grids amounts to about 5 min/pool tail considering that it takes a minute to count fines on one grid.

Given the poor comparability encountered among multiagency grid-count study results even among well-trained crews applying very similar procedures (Roper *et al.*, 2010), improvements in accuracy and precision are highly desirable. Similarly, the wide range of thresholds for fines indicating habitat impairment (Milan *et al.*, 2000) not only reflect different habitat requirements and tolerance by spawning salmonids but are likely attributable to different sampling methods and procedures as well. Hence, the need for accuracy and precision in measured fines, both for monitoring status and trends of streambed fines as well as for assessing impairment of spawning habitat, brings with it the need to employ sampling schemes that provide increased accuracy and precision, even at the cost of increased field time.

CONCLUSIONS

The study demonstrated how bankward fining and longitudinal differences of pool-tail fines can affect amounts, variability, and accuracy of grid-count results obtained by different sampling schemes. Weighing strengths and weaknesses, the All 7 scheme came out as the overall best; Central 5 obtained generally moderate scores, whereas the other three low work-effort schemes typically had only one strong but several weak points. Accuracy and precision of grid count results in pool-tail areas can be improved by using the All 7 scheme.

Given that patchy deposits and lateral fining of pool-tail fines that drive differences among sampling schemes are observable in many pools in coarse gravel-bed mountain streams, the trends of described differences among sampling schemes are general. However, further field investigations to explore patterns and degree of spatial variability of pool-tail fines in various stream types are desirable with the aim of identifying grid-count schemes that yield optimum precision and accuracy in a variety of stream settings. With that, selection of sampling protocols can shift from strict standardization to optimization.

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