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DOWNSTREAM EFFECTS OF DIVERSION DAMS ON SEDIMENT AND HYDRAULIC CONDITIONS OF ROCKY MOUNTAIN STREAMS

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ABSTRACT

Reduced streamflow via flow diversion has the potential to limit the sediment-transport capacity of downstream channels and lead to accumulation of fine sediments and habitat degradation. To investigate, we examined the effects of variable levels of flow diversion on fine-sediment deposition, hydraulic conditions and geomorphic alteration. Our study consisted of a detailed field analysis pairing reaches above and below diversion dams on 13 mountain streams in north-central Colorado and southern Wyoming USA. Diversions are ubiquitous across the American West, yet previous comparative studies on the effects of flow diversion have yielded mixed results. Through application of strict site-selection criteria, multiple fine-sediment measures, and an intensive sampling scheme, this study found that channels downstream of diversions contained significantly more fine sediment and slow-flowing habitat as compared to upstream control reaches. Susceptibility to fine-sediment accumulation was associated with decreasing basin size, decreasing bankfull depth and smaller d_{84}, and it appears to be magnified in streams of less than 3% slope. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: flow diversion; dam; fine sediment; stream management; hydraulic alteration; field methods; habitat degradation

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INTRODUCTION

The modification of flow and sediment regimes by dams is ubiquitous in the United States. Over 82 000 dams exceeding 2 m in height and another 2 000 000 smaller structures substantially alter downstream water and sediment regimes in virtually all watersheds $< 2000\,km^2$ (Graf, 1999; Poff *et al*., 2007; USACE, 2007). In the semiarid western United States, potential degradation of stream habitat associated with flow depletion by thousands of relatively small diversion structures is related to increasing demands on available water. Adding to the challenge, the spatial and temporal distributions of water demand are often inconsistent with natural fresh-water supplies. For example, the majority of precipitation in Colorado falls on the western side of the Continental Divide, while 61% of consumptive use takes place on the eastern side, requiring 24 trans-mountain water diversions across the Continental Divide (Litke and Appel, 1989). There is also a seasonal discrepancy, with the majority of runoff occurring during the spring snowmelt and water use peaking in late summer to early autumn, requiring over 12 750 reservoirs and 56 000 active points of diversion in Colorado alone (CDSS, 2007).

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Flow depletion can fundamentally alter channel hydraulics in small mountain streams. Relative roughness and slow-flowing habitat increase with flow depletion, thereby limiting fine-sediment transport and contributing to in-stream fine-sediment accumulation, which can diminish habitat and water-quality conditions for biological communities (Waters, 1995). According to the U.S. Environmental Protection Agency, 36% of surveyed streams in the western United States suffer from poor or fair substrate condition due to accumulation of fine sediments (EPA, 2006). A handful of studies have attempted to quantify the effects of stream diversion on channel geometry and in-stream sedimentation, with varied results. For example, Wesche *et al*. (1988) examined bankfull channel dimensional and hydraulic properties above and below diversions in southern Wyoming and northern Colorado, and found that the downstream channels of low-gradient streams (< 1.5%) were susceptible to reductions in channel depth, area and capacity, but steeper channels were not. Similarly, in a study of nine small diverted streams in the upper Colorado River basin, Ryan (1997) reported reduced channel widths in unconstrained valley bottoms below diversions, but underscored the resiliency of sub-alpine channels and the periodic flooding that limits channel response. Bohn and King (2000) made a concerted effort to select study sites with minimal variation in slope and valley confinement across the diversion, but found no correlation between stream gradient and channel change. Additionally they reported only subtle reductions in channel conveyance, a varied sediment response and no effects on riparian vegetation. These studies have demonstrated the difficulty of detecting the general physical effects of diversion dams due to the tendency for downstream channel geometry to be maintained by the passage of flood flows and to be located at breaks in stream gradient (i.e. transition from steep, confined channels to gentle, alluvial channels in mountain valleys) with associated changes in geomorphic context.

Diversions also have the potential to change in-stream sedimentation processes, but quantifying this is complicated by high natural temporal and spatial variability of flow and sediment regimes. Further, sediment transport and deposition integrates processes across multiple scales, from the entire basin to individual habitat patches (Knighton, 1998). Sediment deposition is primarily activated by two processes: (1) a change in sediment loading, and/or (2) an alteration in stream hydrology. Sediment flux is a natural occurrence; however, land-use changes can result in a direct alteration of both the quantity of available sediments and the flow available to transport them. Stream sediments come from either the bed and banks of the stream network or from the remainder of the basin, including upland hill slopes, agricultural lands and urban development (Wood and Armitage, 1997). In wet regions such as the Pacific Northwest, fine sediments increase with land-cover alteration and riparian disturbance irrespective of underlying lithology (Kaufmann *et al*., 2009). Even in minimally disturbed basins, the washload (silt, clay and fine sand particles) that is continuously delivered and transported through drainage networks across a wide range of flows provides a continuous source of sedimentation potential (Gordon *et al*., 2004).

Sediment accumulation spurred by an increase in sediment supply has been shown to homogenize bed texture, decrease average particle size and diminish geomorphic heterogeneity (Buffington and Montgomery, 1999; Bartley and Rutherfurd, 2005). Laboratory flume studies demonstrate progressive increases in surface fines content at higher levels of flow extraction (Parker *et al*., 2003) and reduced hydraulic conductivity due to substrate clogging that only flushes at moderately large floods (Schalchli, 1992). Fine sediments also alter bed mobility by increasing transport with greater levels of sand content (Jackson and Beschta, 1984; Wilcock, 1997).

Streamflow diversions often produce extended drought-like periods, with lower flow volume and velocity. These conditions coupled with higher water temperatures and less flow connectivity, lead to the reduction of benthic habitat area and quality (Miller *et al*., 2007). Multiple studies have investigated the relationship between flow diversion and aquatic insect communities(Castella *et al*., 1995; Boulton, 2003), including a study in the Rocky Mountains (Rader and Belish, 1999). The responses have been varied (as reviewed in Dewson *et al*., 2007). One key to better understanding the effects of flow diversion on biota is learning how hydrologic change modifies channel sedimentation and flow conditions. Our goal was to measure this change in terms that could be related to aquatic habitat.

While the biological implications of fine sediment and flow diversion have been well studied, only a paucity of studies has assessed the direct physical and hydraulic effects of flow diversion. Given the large number of stream diversions and the negative impact of stream sedimentation, a better understanding of the effects of flow diversion could enable the construction and management of flow diversions such that downstream sedimentation could be mitigated. In this study, we address this gap in knowledge by investigating the downstream hydraulic, sedimentary and geomorphic effects of diversion dams on small streams, with particular focus on multiple measures of fine sediment.

Study description and objectives

Searching for a greater understanding of the downstream hydraulic, sedimentary and geomorphic influence of diversion dams, our specific objectives were to: (1) quantify and compare a multitude of measured and computed channel characteristics above and below diversions operating across a gradient of flow diversion from minor to complete, (2) identify the predominant factors contributing to fine-sediment accumulation in diverted streams and (3) to compare the utility of multiple fine-sediment measurement techniques. In the summer and fall of 2005, we quantified the effects of agricultural and municipal diversion from 13 Rocky Mountain streams. We selected diversion sites of similar channel characteristics between a reference reach above the diversion and a representative reach below the diversion using strict site-selection criteria to minimize inherent geomorphic differences prior to diversion construction. A detailed quantification of the hydraulic, sedimentary and geomorphic characteristics both above and below diversion dams allowed us to assess the effects of diversion structures and flow diversion on the physical and ecological conditions of diverted streams, both on the current wetted channel and on the bankfull channel. Accordingly, we focused on three hypotheses:

Hypothesis 1: *As compared to geomorphically similar reference reaches, stream reaches below diversion structures have significantly higher levels of fine sediments when quantified by multiple fine-sediment measurement techniques.*

Hypothesis 2: *Downstream reaches have significantly different bankfull and wetted dimensional, hydraulic*

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and habitat characteristics as compared to upstream reference reaches.

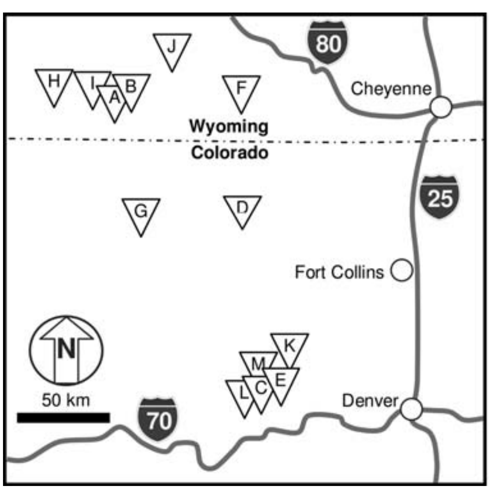
Hypothesis 3: *Greater accumulation of fine sediments due to flow diversion will occur in channels with some combination of (1) lower gradient, (2) higher hydraulic roughness, (3) greater amounts of flow blockages, (4) higher proportion of flow diverted or (5) basins with a greater sediment supply.*

METHODS

The detailed field and laboratory methodology described below was designed to overcome some limitations of previous studies and highlight effects of diversion dams on stream hydraulic and physical condition. The study design reflected a balance between achieving a sufficient number of field sites and adequate detail at each site. Detailed physical surveys of 26 reaches were performed pairing upstream control reaches with downstream diverted reaches at the 13 study sites in northern Colorado and southern Wyoming (Figure 1). All diversion dams were located on U.S. Forest Service land and were dispersed among the Williams Fork, Fraser, North Platte, Laramie and Little Snake river basins. The construction and materials of the low-head diversion dams in this study varied widely, from seasonally constructed rock, wood and tarp structures to permanent concrete dams with multiple gates and spillways. Most of the dams are primarily for agricultural use, but five of the diversions, in the Fraser River and Williams Fork River basins, are operated by Denver Water for municipal use.

Often diversion dams are constructed at points of change in valley confinement and slope, thus alterations due to the structure are often overshadowed by reach-scale differences in the stream prior to dam construction. Therefore, it was critical to select sites with matching stream character across the diversion dam. Previous work analysing the effects of flow diversions (Wesche *et al*., 1988; Ryan, 1997; Bohn and King, 2000) underscored the dominance of antecedent stream and valley conditions and the need for careful selection of comparison reaches. Accordingly, available diversion records and area maps were used to identify candidate diversion sites with relatively minimal anthropogenic land-use alteration and no flow diversions or augmentations in the upstream drainage basin. During on-site visits, the collective engineering and ecological judgement of our research team assessed the reach-scale similarities above and below each diversion, focusing on bed slope, channel planform, stream type, valley confinement, vegetative influences and lithology. If we concluded that the study reaches varied fundamentally in these features before the construction of the diversion dam, the site was rejected.

The effects of diversion magnitude were studied by selecting sites that were likely to operate for the duration of the study season (early summer to mid-fall) across a gradient of base-flow diversion from minor to complete. Lack of control over the diversion operation and seasonal access restrictions prevented the research team from measuring all streams in both the summer and fall seasons. Initial field visits were performed on 11 streams in July on the lower end of the falling limb of the snowmelt hydrograph and final visits on 7 of the 11 original streams, plus two additional streams in September and October at base-flow conditions, resulting in a total of 20 stream visits (Table I). As basins of minimal upstream anthropogenic alteration tend to be high in elevation in this region, selected diversion sites were all above 2300 m. The steep, clear-water study streams were characterized by high sediment-transport capacity and comparatively low fine-sediment supply from spruce-fir-dominated watersheds.



Key	Code	Site Name	Elevation (m)
A	BCO	Billie Creek One	2747
B	BCT	Billie Creek Two	2748
C	BOB	Bobtail Creek	3185
D	CAN	South Fork Canadian River	2671
E	CUR	Current Creek	3463
F	FOX	Fox Creek	2299
G	GRZ	Little Grizzly Creek	2595
H	HAG	Haggerty Creek	2574
I	MIN	North Fork Miners Creek	2557
J	NFR	North French Creek	2916
K	RAN	Ranch Creek	2894
L	SMN	Steelman Creek	3184
M	STL	St. Louis Creek	2824

Figure 1. Map of stream diversion sites and elevations included in this study

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Table I. Study site sample times and conditions

Site code	Site name	Basin area (km^2)	Summer	Fall	Visit code	Above/ below diversion	Flowrate, Q (^{L}/s)	Bed slope, So (m/m) (%)	Wetted width (m)	Median sediment size, d_{50} (mm)	% Slow (pool) habitat
BCO[a]	Billie Creek One	2.80	x		BCO_1	Above	41.3	7.2	2.03	20.6	16
						Below	0.4	4.7	0.69	10.9	32
BCT[a]	Billie Creek Two	2.21	x		BCT_1	Above	37.9	2.7	1.78	19.6	0
						Below	0.5	3.3	1.39	13.5	47
BOB	Bobtail Creek	14.28		x	BOB_2	Above	73.2	3.3	3.81	68.7	0
						Below	2.9	4.6	2.20	78.4	55
CAN	South Fork Canadian River	4.89	x		CAN_1	Above	178.8	1.7	3.68	24.8	39
						Below	138.4	1.3	3.52	5.1	5
				x	CAN_2	Above	36.8	1.7	2.66	24.8	44
						Below	10.7	1.3	2.31	5.1	16
CUR	Current Creek	1.08	x		CUR_1	Above	36.0	14.5	2.31	124.0	15
						Below	3.3	15.7	1.34	54.3	58
				x	CUR_2	Above	5.8	14.5	2.28	124.0	0
						Below	2.1	15.7	1.39	54.3	30
FOX	Fox Creek	94.68	x		FOX_1	Above	66.9	1.4	4.56	11.8	15
						Below	2.8	2.9	1.92	41.6	44
GRZ	Little Grizzly Creek	27.38	x		GRZ_1	Above	358.5	2.4	5.87	116.0	0
						Below	243.3	2.1	4.56	91.9	13
				x	GRZ_2	Above	67.6	2.4	4.10	116.0	4
						Below	5.5	2.1	2.36	91.9	60
HAG	Haggerty Creek	19.70	x		HAG_1	Above	332.4	2.9	7.28	96.7	18
						Below	138.0	3.3	4.31	61.0	0
				x	HAG_2	Above	70.5	2.9	6.30	96.7	11
						Below	2.3	3.3	2.58	61.0	40
MIN	North Fork Miners Creek	6.35	x		MIN_1	Above	101.6	10.4	4.33	50.3	29
						Below	38.1	10.0	1.81	54.7	72
				x	MIN_2	Above	13.1	10.4	3.91	50.3	43
						Below	1.7	10.0	1.63	54.7	70
NFR	North French Creek	16.89	x		NFR_1	Above	368.9	3.7	8.06	103.4	2
						Below	0.3	3.1	2.29	119.7	46
				x	NFR_2	Above	110.6	3.7	6.85	103.4	9
						Below	7.0	3.1	2.56	119.7	17
RAN	Ranch Creek	8.08	x		RAN_1	Above	180.9	10.6	3.41	38.8	69
						Below	138.2	7.1	3.25	99.1	8
SMN	Steelman Creek	9.38		x	SMN_2	Above	52.6	6.3	3.67	99.3	0
						Below	7.5	3.9	2.78	77.5	27
STL	St. Louis Creek	34.15	x		STL_1	Above	670.9	1.9	6.34	75.9	2
						Below	224.7	1.8	5.64	76.1	3
				x	STL_2	Above	190.8	1.9	5.80	75.9	0
						Below	102.4	1.8	5.30	76.1	0

[a]Billie Creek One (BCO) and Billie Creek Two (BCT) are two separate upstream branches of the main stem of Billie Creek.

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Reach and habitat characterization

The essence of this study was to compare the reference upstream reach condition with the diverted downstream reach condition across all sites. Study-reach length was selected to be approximately 16 times the bankfull width of the upstream reference channel and was divided into eight equally spaced transects.

Habitat variation within each of the 26 reaches was characterized by the linear distribution of habitat types along each of the eight transects. The Hawkins *et al*. (1993) hierarchical classification of sub-reach habitat types was used to first divide stream units into fast and slow water (Level I), then further parse fast water into turbulent versus non-turbulent and slow water into scour versus dammed pool (Level II). The Level II classification scheme was initially employed, but variation among study sites required simplification to Level I; thus the field-recorded riffles, runs and cascades were grouped into a 'fast' category and pools were classed in the 'slow' category. Specifically, any section of stream containing moderate to rapidly moving flow and surface disturbances was classified as a fast habitat zone, whereas slow habitat zones were demarcated by a smooth water surface and relatively slow flow velocity. The habitat unit distribution along each transect was summed across all eight transects and then transformed to represent the proportion of each habitat unit reach wide. Some study reaches, namely plane-bed streams that do not characteristically have pools, were identified by this protocol as having no slow-flowing habitat. Yet, slow habitat sediment samples were taken from metre-scale slow patches along the margins of the channel.

The various dimensional, hydraulic and textural properties of each stream were measured at multiple scales. Large-scale (cross section to reach) characteristics were recorded with physical measurements and habitat characterization, but smaller scale characteristics were analysed using local streambed surface and subsurface sampling within fast- and slow-flowing habitat units. Each of the eight transects was measured for wetted and bankfull widths in addition to the depth, velocity and location of the thalweg. The downstream profile and two cross sections, representative of the reach as a whole, were surveyed using an auto-level to determine channel slope and wetted and bankfull cross sectional characteristics.

Discharge was measured using the velocity-area cross-section method (Harrelson *et al*., 1994). Depth-averaged velocity was measured with a Marsh McBirney Flo-Mate™ portable flow metre on a calibrated wading rod at greater than 10 equally spaced points across the channel. The mean of two cross-sectional-averaged flows determined the reach-averaged value. Additionally, point measurements of flow depth and depth-averaged velocity were recorded at each substrate sampling site and at the thalweg of each cross section. Locating small streams in Colorado and Wyoming with gauges both upstream and downstream of a diversion, (that also met our selection criteria) proved infeasible for all sites, owing to the disproportionate distribution of USGS (U.S. Geological Survey) streamflow gauges towards larger streams and rivers (Poff *et al*., 2006). As such, time-series streamflow data were not available and we had to rely on measurements taken during field visits. On-site flow measurements at site and auto-level survey visits suggest that diversion rates did not vary substantially during the operation season; leading to an assumption that instantaneous measurements of flow conditions were sufficiently representative of average conditions over the duration of the study.

In the absence of historical data, we focused on three types of diversion measures including: (1) fraction of flow per measured width of channel, (2) flow depth scaled to a representative coarse-sediment diameter and (3) flow below the diversion relative to that of the control reach upstream. Unit discharge (q), which scales the cross-sectional discharge by the wetted width, effectively describes the volumetric flow per unit width of channel. Relative submergence (R/d_{84}) is defined as the ratio of the hydraulic radius (R) to the 84th percentile sediment size (d_{84}); as flow depth increases the ratio increases into the range between 1 and 4, beyond which wave drag markedly decreases and particle roughness is minimal (Bathurst, 2002). Per cent diverted (DIV) is a straightforward measure of the difference between the upstream and downstream flow.

An extensive set of standard hydraulic descriptors were calculated using the basic measurements of channel form, flow characteristics and sediment summary metrics. We developed a suite of three independent fine-sediment measures with the aim of providing greater resolution than many standard protocols (e.g. Faustini and Kaufmann, 2007). Specifically, fine sediment, defined in this project as sediments less than 2 mm in diameter (including sand, silt and clay), was measured using three intensive methods:

(1) The surface sediment of each reach was quantified using a 400-point pebble count distributed across the eight transects. Fifty pebbles located under grid intersections of a sampling frame were selected and measured with a gravelometer. (Bunte and Abt, 2001). The sampling grid was set to intervals greater than the largest particles of each reach to minimize the possibility of selecting any single particle more than once.
(2) Three points in the fast- and slow-flowing habitat of each reach were selected for local cylinder sampling of fine sediment. The fast habitat samples were limited to areas where a steel cylinder could be driven into the bed and the slow habitat samples avoided any heavy patches

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of algae or the channel margins when possible. At each location, a 0.25 m diameter steel cylinder was hand-driven up to 15 cm into the bed. Where the cylinder would not penetrate the bed to an acceptable depth, a ring of open-cell foam helped to seal the cylinder to the streambed. Within the cylinder, the bed was agitated and an aliquot sample was removed from the water column. Next, samples were collected to a depth of approximately 10 cm and field-separated into ± 6 mm sizes. The coarser fraction was drip dried and weighed on-site and the finer fraction was sieved in the laboratory at 5.6, 2, 0.5 and 0.25 mm intervals. The combined portion finer than 2 mm plus the suspended solids from the aliquot sample were summed and then used to calculate the per cent mass fines per specified volume of sediment. These measures will be reported below as 'volumetric per cent fines.'

(3) Finally, a local-scale surface presence/absence areal count of fine sediment was performed with the grid sampler proximal to all cylinder sampling locations. Fifty points were noted at each of the six sampling locations, for a total of 300 points per reach.

All sediment measures are expressed as the per cent of fine sediment for ease of comparison. The areal and pebble-count measures are a per cent of a total count of particles and the volumetric measure is a per cent of mass extracted from the cylinder sample.

In addition to qualitative field observations of bed and bank stability at each study site, a larger spatial analysis of the lithology and sediment availability of the upstream drainage basins was performed by identifying the dominant underlying surface geology of the basins upstream of each diversion structure (Green, 1992; Green and Drouillard, 1994) using maps generated in ArcGIS™ 9 (Environmental Systems Research Institute, Inc. (ESRI), Redlands, California, USA). The predominant lithology of each largely undisturbed basin was then stratified based on its sedimentation potential (Reid and Dunne, 1996).

The site-specific backwater extent and permeability of individual diversion dams could highly influence fine sediment and flood passage. Indeed, the construction and materials of diversion dams was observed to vary widely, from seasonally reconstructed rock, wood and tarp structures to permanent concrete dams with multiple gates and spillways. To limit local effects, reaches were located a sufficient distance upstream and downstream of the diversion structure to eliminate any local backwater or scour effects.

Data analysis and statistics

Survey results for cross-sectional and longitudinal data were post-processed using Microsoft Excel® spreadsheets and Visual Basic® routines (Microsoft, Redmond, Washington, USA). Channel slope was calculated by fitting a linear trend line to the measured water–surface elevations for each reach. Additionally, cumulative distribution functions of pebble counts were calculated and summarized as descriptors of sediment distribution (d_{16}, d_{50} and d_{84}).

All parameters measured in the field as equal to zero (i.e. no fine sediment in a grid count, or zero velocity as read by the flow meter) were adjusted to one-half of the detection limit for analysis. Statistical calculations were performed using SAS® 9.2 (2008, SAS Institute, Inc., Cary, North Carolina, USA). Parameters of both above and below diversion channel characteristics were tested for normality. Due to the tendency for small sample sizes ($n = 20$) to pass parametric normality tests, analysis shifted to the more critical graphical evaluation of quantile–quantile plots and histograms. Investigation of these graphs of all 41 variables led to the conclusion that non-parametric statistical testing would be appropriate.

The upstream versus downstream comparisons of the 20 site visits were evaluated with the non-parametric, one-tailed, Wilcoxon signed rank test at $\alpha = 0.10$ level. For a posteriori verification of channel similarity above versus below each diversion dam, we analysed the differences in the water–surface slope and d_{50} between the upstream and downstream study reaches. Similarly, to test the hypothesis that diversion dams cause significant changes in channel physical and hydraulic characteristics between the upstream control reach and the downstream diverted reach, Wilcoxon signed rank tests of the differences in channel dimension, substrate, hydraulics and habitat variables from below the diversion to above were performed. The data set was also split into two equal sized groups of 10 site visits apiece, coinciding with $\pm 3\%$ slope, to investigate whether low-gradient streams subject to flow diversion are more susceptible to fine-sediment accumulation.

Multiple methods were examined to express the difference in fine-sediment accumulation between the reference upstream and diverted downstream reaches. Preliminary regression analyses focused on fine-sediment variables expressed as a per cent change in sediment from above to below the structure. However, low values for percentage of fine sediment in the control reach at some sites resulted in a very small divisor in the per cent-change relationship. This numerical issue caused multiple order-of-magnitude differences in parameter values which led to extreme outliers for regression analysis. Instead, an arithmetic difference between the per cent fines downstream and upstream of the diversion was used. It is acknowledged that the application of this simple difference does not normalize systems with greater or lesser overall amounts of fine sediment; hence two sites would have a 5% difference in fine sediment whether they contained 30% upstream and 35% downstream or 1% upstream and 6% downstream.

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To examine whether hydraulic and geomorphic factors explain significant variance in fine-sediment accumulation in both fast- and slow-flowing habitat patches, our regression analysis consisted of multiple steps. As 41 variables were either directly measured in the field or calculated from field-measured values; it was necessary to reduce candidate descriptors to those that contained unique, non-redundant information with a straightforward physical interpretation. First, principal components analysis (PCA), using SAS® 9.2, was used to reduce redundancy among parameters and extract the variables that contained the most unique information (Jolliffe, 2002). A reduced set of orthogonal PCA axes did not lend itself to clear interpretation, thus field-measured and latent variables were preserved. Next, seven variables were selected for best subsets regression analysis (SAS® 9.2) using the information from the PCA analysis and physical understanding as to which variables could provide information about susceptibility to fine-sediment accumulation and be easily measured (Table II). All dependent variables (fine sediment and habitat condition) were represented as the difference between the downstream and upstream condition and independent variables as the value in the upstream channel. Regression models were sorted by Mallow's Cp ranking. We then selected representative regression models on the basis of their physically interpretability, statistical significance and response direction of included variables.

RESULTS

Reach comparison

The 13 study sites (paired reaches) are located in mountainous terrain, exhibit snowmelt hydrology, and have gravel to cobble beds with d_{50} between 5 and 124 mm. Flow diversion ranged from 23 to 99% of the upstream flow during field visits and water surface slopes varied between 1.3 and 15.7% (Table I).

The Wilcoxon signed rank tests showed, in response to our first hypothesis, reaches below diversion dams contain higher levels of fine sediment than those above. Four of five fine-sediment metrics exhibited significant increases in fine sediment in the downstream reach, with the exception of volumetric fines in slow-flowing zones ($p = 0.763$). Additionally, downstream diverted reaches had significantly more slow habitat ($p = 0.048$) than upstream reference reaches and slow-zone volumetric and areal samples had a significantly higher percentage of fines than fast-zone samples ($p < 0.001$). The subset of 10 channels with less than 3% slope contained significantly more downstream fine sediment by both the pebble count ($p = 0.094$) and volumetric fines in fast-zone ($p = 0.004$) measurements, whereas the steeper channels ($\geq$3%) did not exhibit any significant differences in fine sediment.

Table II. Variables included in best subsets analysis to predict changes in fine-sediment levels across diversion structures

Variable	Variable abbreviation	Units
Per cent of flow diverted	Div	%
Bankfull dimensionless shear stress	τ^*	—
Drainage basin area	Basin	km^2
Unit discharge	q	m^2/s
Bankfull depth	D_bf	m
Darcy's friction factor	f	—
84th percentile grain size	d_{84}	mm

Addressing the second hypothesis, upstream and downstream reaches would significantly vary in dimensional and hydraulic characteristics, 32 of 41 measured or calculated variables differed significantly ($p < 0.10$) between upstream and downstream reaches. This included significant downstream declines in the hydraulic variables of flow velocity ($p < 0.001$), average shear stress ($p = 0.002$) and unit stream power ($p < 0.001$), even with stream type, slope and channel character matched across the diversion sites (Table III).

Channel slope ($p = 0.54$) and channel substrate (d_{50}) ($p = 0.15$) were not significantly different between the reaches above and below the diversion, confirming that paired sites were fundamentally similar prior to diversion construction. The independence of the 11 summer and nine fall field visits (with seven sites visited in both seasons) was tested using a parametric mixed effects model to examine the viability of using a single data set of $n = 20$. This mixed model tested the influence of both site location and seasonality on the regression results. Three of the four local fine-sediment measures showed no seasonal effect, with only areal fines in the slow zones showing a marginal seasonal effect ($p = 0.092$). No site effect was detected in three of the four sediment measures with the exception of volumetric fines in the fast zones ($p = 0.032$). With limited seasonal and site effects, it was concluded that combining all site visits into a single data set of $n = 20$ would be appropriate (P. Chapman, Colorado State University, Department of Statistics, personal communication, 2009).

Regression analysis

Predictors for change in fine sediment between the downstream and upstream reaches were dominated by inverse relationships with upstream bankfull depth, basin size and d_{84} (Table IV). Change in volumetric fines in fast-flowing zones showed a strong negative relationship with d_{84}. Change in volumetric fines in slow zones, not found to be significantly different across study sites in Wilcoxon signed rank tests, likewise had no significant

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Table III. Results from Wilcoxon signed rank test of differences between upstream reference reach and downstream diverted reach[a]

Variable	Units	Response direction (below–above)	All sites	Low slope (<3%, $n = 10$)	High slope (>3%, $n = 10$)
Volumetric % fines—fast	-	+	**0.002**	**0.004**	0.242
Volumetric % fines—slow	-	+	0.763	0.625	0.432
Areal % fines—fast	-	+	**0.044**	0.193	0.131
Areal % fines—slow	-	+	**0.074**	0.160	0.232
Pebble count % fines[b]	-	+	**0.052**	**0.094**	0.438
Proportion slow	-	+	**0.048**	0.383	**0.084**
Bed slope[b]	m/m	–	0.588	0.563	0.297
Flow rate	m^3/s	–	< **0.001**	**0.002**	**0.002**
Wetted width	m	–	< **0.001**	**0.002**	**0.002**
Unit discharge	m^2/s	–	< **0.001**	**0.002**	**0.010**
Cross-sectional area	m^2	–	**0.014**	0.106	**0.084**
Hydraulic depth	m	–	0.210	0.570	0.232
Hydraulic radius	m	–	**0.004**	0.106	**0.027**
Wetted perimeter	m	–	**0.015**	**0.049**	0.131
Bankfull width[b]	m	–	**0.011**	**0.063**	0.156
Bankfull area[b]	m^2	–	**0.040**	**0.063**	0.297
Bankfull depth[b]	m	–	0.216	0.313	0.469
Average Velocity	m/s	–	< **0.001**	**0.002**	**0.027**
Shear velocity	m/s	–	**0.003**	**0.065**	**0.027**
Shear stress	N/m^2	–	**0.002**	**0.049**	**0.037**
Dimensionless shear stress	-	–	0.231	0.770	**0.065**
Particle Reynolds number	-	–	**0.004**	**0.037**	**0.049**
Reynolds number	-	–	< **0.001**	**0.002**	**0.010**
Froude number	-	–	< **0.001**	**0.004**	**0.037**
Grain Froude number	-	–	**0.004**	0.106	**0.020**
Average stream power	W/m	–	< **0.001**	**0.002**	**0.002**
Unit stream power	W/m^2	–	< **0.001**	**0.002**	**0.004**
Dimensionless unit stream power	-	–	**0.047**	0.695	**0.010**
'Manning's roughness	-	+	**0.001**	**0.020**	**0.049**
Average thalweg depth	m	–	< **0.001**	**0.006**	**0.002**
Average thalweg velocity	m/s	–	**0.001**	**0.020**	**0.027**
Average sediment size[b]	mm	–	0.497	0.438	0.938
84th Percentile sediment size[b]	mm	–	0.340	0.844	0.375
Relative submergence R/d_{50}	-	–	0.368	0.695	**0.065**
Relative submergence R/d_{84}	-	–	**0.033**	0.322	**0.037**
Average depth—fast	m	–	**0.081**	0.680	**0.027**
Average depth—slow	m	–	0.504	0.443	0.752
Average velocity—fast	m/s	–	**0.015**	0.770	**0.002**
Average velocity—slow	m/s	–	**0.001**	**0.031**	**0.047**
Unit discharge—fast	m^2/s	–	**0.040**	0.846	**0.002**
Unit discharge—slow	m^2/s	–	< **0.001**	**0.023**	**0.006**

Note: bold values significant at a $p < 0.10$.
[a]Please see Gordon *et al*. (2004) and Garcia (2008) for variable definitions and equations.
[b]These variables were calculated with site sample set of $n = 13$ due to the measurements being performed only once, not for each field visit.

regression models. A few weak relationships with change in volumetric fines in slow zones were initially reviewed, but removal of an outlier (CAN_1) eliminated all significant relationships. Change in pebble-count fines had consistent inverse relationships with upstream bankfull depth. Finally, the percentage change of slow habitat showed a strong positive relationship with per cent diverted. Shifts in R/d_{84} and unit discharge were also considered as measures of flow diversion, but neither proved significant in regression models. Power models yielded no substantial improvements over linear models.

The results from the regression analysis enabled us to address our multi-part third hypothesis, that various channel and basin factor(s) influence fine sediment accumulation. As such, we did find differences in fine-sediment response between sites greater and less than 3% slope, yet slope of the upstream reach was not found significant as a continuous variable predicting fine-sediment deposition across sites.

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Table IV. Representative regression models

Dependent variable	Representative regression models	Model p-value	Adjusted R^2	β_1 p-value	β_2 p-value
Change in volumetric % fines—fast	$0.0301–0.109^*d_{84}$	0.011	0.26	0.011	—
Change in volumetric % fines—slow	no significant models				
Change in areal % fines—fast	$0.479–1.068^*$D_bf	<0.001	0.57	<0.001	—
Change in areal % fines—slow	$0.591–0.0089^*$Basin$–1.647^*d_{84}$	0.006	0.39	0.005	0.034
Change in pebble count % fines	$0.221–0.491^*$D_bf	0.001	0.56	0.001	—
Change in slow habitat %	$-0.507+0.893^*$Div	<0.001	0.56	<0.001	—

Note: All dependent variables expressed as (% below diversion)–(% above diversion) and independent variables are identified in Table II.

Additionally, no significant models were found relating channel Darcy's friction factor (a measure of average roughness) or ratio of wetted channel width to d_{84} (as an indicator of blockage potential) to any of the fine-sediment measures. Higher proportion of flow diverted was related to increases in slow habitat (as previously noted), but not to changes in any of the fine sediment metrics. Similarly, we found no indication that geologic settings are associated with levels of fine sediment below diversions, although we could not rigorously test this with the available data set.

Fine-sediment metrics

Differences in volumetric and areal per cent fines varied in magnitude, but tended to follow consistent patterns at individual study sites. Sites with more or less fine sediment in the downstream reach as compared to the upstream reference reach had fairly consistent positive or negative differences (respectively) across the five local fine-sediment measurements (Figure 2).

The areal per cent fines measure yielded a greater percentage of fines than the volumetric measurement in the majority of study reaches. In fast-flowing zones, the areal measure yielded a greater amount of fines than the volumetric measurement in 28 of 40 study reaches, with an average measurement of 16.2% more fines. Slow zones were estimated to have a greater amount of fines via areal measurement in 38 of 40 study reaches, with an average of 53% more fines than the volumetric measurement. Interestingly, both methods measured a similar level of variability, with fast/slow coefficients of variation (CV) of 1.34/0.82 for the areal measurements as compared to 1.04/0.81 for the volumetric measure. Fast-flowing zones had higher CVs than slow-flowing zones for both areal and volumetric measures.

The central hypothesis that fine sediments would increase downstream of diversion dams was confirmed, but the actual percentage of downstream reaches having a greater amount of fine sediment varied depending on measurement technique. Eighty per cent of streams contained more fine sediment downstream when measured volumetrically in fast-flowing zones as compared to 50% of streams having more downstream sediment when measured volumetrically in slow-flowing zones. Areal measures detected more fine sediment below diversion dams in both fast and slow habitat at nearly 70% of study sites. Wilcoxon signed rank test showed that fast-flowing zones had significantly higher average velocities ($p = 0.001$) than slow-flowing zones, yet slow-flowing zones had greater depths 60% of the time (non-significant, $p = 0.50$). Slow-flowing zones also contained significantly more volumetric ($p < 0.001$) and surficial ($p < 0.001$) fine sediment than fast-flowing zones.

Sediment supply

As a surrogate for direct measures of sediment supply, several local and basin conditions were analysed. Study-site stream banks and beds were observed to be stable, with little evidence of localized mass wasting and minimal suspended load during low-flow conditions. The collective geology of the study-site drainage basins is a mix of Precambrian and Quaternary igneous and metamorphic material, with some glacial deposits. Cross comparison of dominant basin rock types and geologic history did not reveal specific basins with a substantially greater potential for fine-sediment production than others.

DISCUSSION

A combination of three key factors provides a weight of evidence of increased fine sediment downstream of diversion dams: (1) a greater amount of fine sediment using both volumetric and areal measures within fast-flowing habitat, (2) more fines in slow habitat as compared to fast, and (3) a shift towards additional slow-flowing habitat in diverted streams. In contrast to earlier studies that struggled to discern significant changes in both channel form and sediment response related to flow diversion (Wesche *et al.*, 1988; Ryan, 1997; Bohn and King, 2000), this study detected several significant shifts in fine sediment, channel form and hydraulics. As our site-selection criterion that study sites were of similar character above and below the

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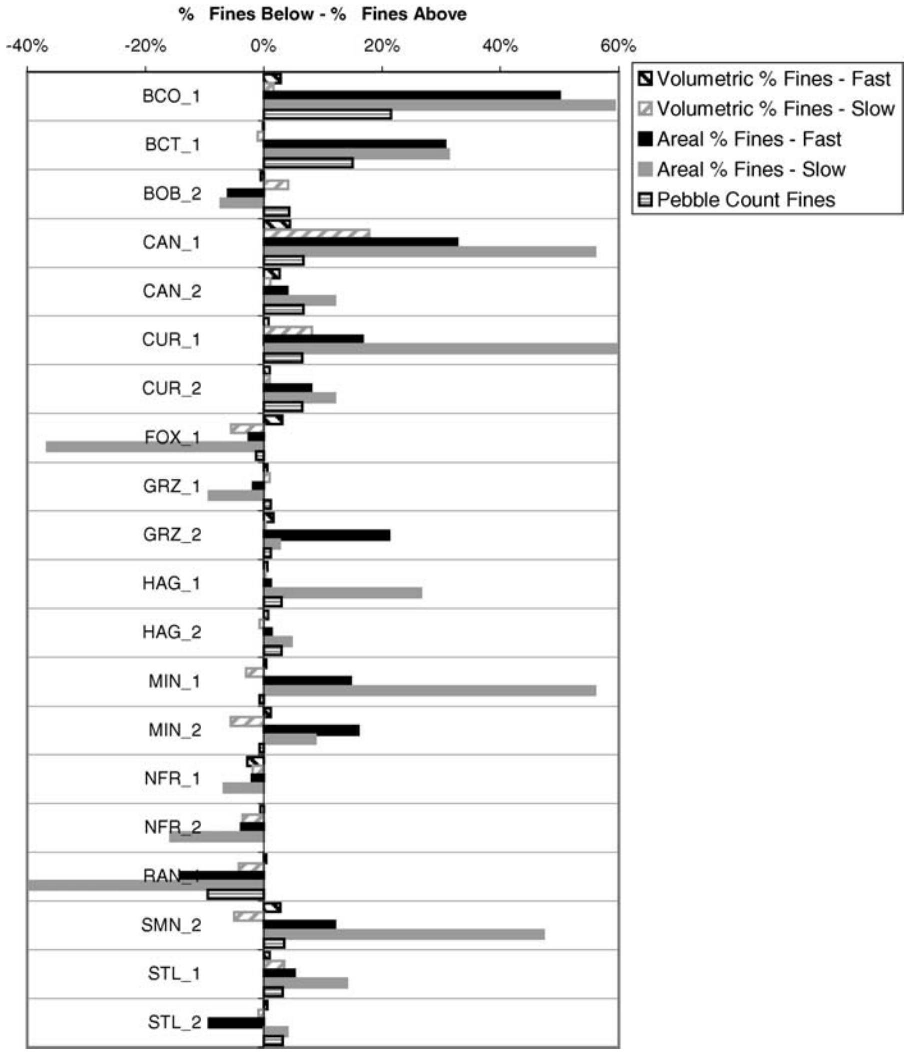

Figure 2. Difference in per cent fines between downstream diverted reach and upstream reference reaches

diversion was supported (as shown by consistent slope and grain-size measurements—Table III), we attribute these shifts to the effects of stream diversion. We found significantly more fine sediment below diversion dams based on multiple measurement techniques. This finding contrasts to results from a previous diversion study of similar stream types (Bohn and King, 2000), where no significant difference was detected in the per cent substrate less than 2 mm based on a 100-particle pebble count. Surprisingly, we were unable to detect any difference in volumetric fines deposited in slow-flowing habitats in this study, but this could have been due to the greater proportion of fine sediments accumulated in pools than fast-flowing habitats and possible inconsistent cylinder-sampling depth to recover representative portions of fine-bed sediments.

Additionally, there were significant differences between various physical and hydraulic characteristics between the upstream reference reach and the downstream diverted reach, as indicated by significant differences in 32 of 41 observed and latent variables (Table III). Further, unlike Ryan (1997) who was unable to detect morphological changes (as indicated by bankfull width) in channels other than wider pool-riffle streams, we detected differences between the upstream and downstream channel bankfull width across all sites ($p < 0.001$), possibly due to a larger sample size or more stringent site-selection criteria. We acknowledge the possible influence of climatic shifts between earlier studies and our own, as the early 2000s were characterized by severe drought conditions in the Upper Colorado River Basin (Woodhouse and Lukas, 2006). Furthermore, the lack of gauge data and diversion history preclude the analysis of the impact of diversion patterns, historical age of diversion or long-term channel alteration. Additionally, the short duration of this study limits the

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extrapolation of reported channel conditions to multiple seasons or years. Yet, the baseflow conditions evaluated in this study persist for the majority of the year, supporting the bearing of our findings on water quality and aquatic biota.

Our statistical models suggest that small streams appear to be more susceptible to fine-sediment accumulation than larger streams, in that we found fine sediment to increase significantly below diversions in response to decreasing basin area, reduced bankfull depth and smaller d_{84} (Table IV). Although fine sediments are readily winnowed by energetic flows (Lisle and Hilton, 1999), in low-flow years trans-basin diversions often reduce peak flows up to 45% (Ryan, 1997). The susceptibility of small streams to fine-sediment accumulation suggests that removal of equivalent proportions of water from small and large streams may have a disproportionately larger effect in smaller channels due to a higher surface area to volume ratio and the resulting greater influence of boundary and bank roughness.

The inverse relationship between d_{84} and fine-sediment accumulation appears to indicate that diverted streams with bed-material loads composed of smaller particles are more prone to fine-sediment accumulation. Buffington and Montgomery (1999) argued that mountain streams receiving relatively high supplies of fine sediment should have higher bankfull dimensionless shear-stress values. We were unable to directly measure sediment supply in this study; however, we did find that bankfull dimensionless shear stress (referenced to d_{84}) decreased with basin size ($p = 0.016$, Adjusted $R^2 = 0.24$). Although we calculated the total bankfull shear stress (as opposed to partitioning the grain shear fraction for the channel bed), the inverse relationship suggests that the streams draining smaller basins in this study may receive higher loading of finer distributions of sediment. Interestingly, we found no association between basin size and the prevalence of 'soft' rock types or glacial material that might serve as sediment sources. An alternative explanation is that the hydrographs of small snowmelt-dominated basins would have steeper falling limbs than larger basins, resulting in more well-sorted surface sediments, including fines (Hassan *et al.*, 2006).

The change in per cent fines and d_{84} each quantify aspects of the sediment distribution, yet d_{84} is principally independent from the change in per cent fines for two reasons. First, the dependent variable, change in per cent-fine sediment, is normalized to the per cent sediment in the upstream reference reach, whereas the independent variable d_{84} is a direct measure of the sediment in the upstream reach. Second, when d_{84} is recalculated after truncating fines from the sediment distribution it is still significant ($p < 0.052$) in predicting change in fine sediment. With respect to the influence of diversion structural design on the capacity to pass fine sediment and high flows, the loss of too many degrees-of-freedom from the categorical ratings prevented statistical analysis within an already limited sample set. As large permanent diversion structures would be more effective than smaller temporary structures at capturing the peak-flow events, it is possible that these large structures would also capture and divert more fine sediments, though no evidence of this correlation was found at the seasonally low flows observed during this study.

The significant variation in fine sediment accumulation between channels >3% slope and those ≤3% seem to signal a threshold response of greater susceptibility of low-gradient channels to fine-sediment accumulation. This threshold response is consistent with the findings of Wesche *et al.* (1988), but a lack of sites less than 1.5% slope in this project precluded direct comparison at the same level. Beyond this slope, the lack of evidence in support of the third hypothesis , could be due to the overall small data set, the pristine nature of the study basins or the distribution of slopes and roughness characteristics of the study sites. In general, the regression models developed in this study provide insight into factors that may predispose streams to fine-sediment accumulation due to flow diversion, but more robust and transferable predictive models are precluded by a limited data set of 20 site visits, as well as the lack of a fully randomized site-selection process.

Ecological implications

A strong positive relationship between per cent diversion and slow habitat ($p < 0.001$, Adjusted $R^2 = 0.56$) (Table IV) suggests that as more flow is extracted from streams, there is a greater shift from turbulent, well-mixed waters to tranquil conditions. No significant differences were found in point measurements of water temperature or dissolved oxygen content between the upstream and downstream channels, most likely due to the proximity of the diverted study reaches to upstream reference conditions. However, a shift in macroinvertebrate composition away from rheophilic (or flow-loving) taxa was found at around 90% diverted in a companion study (Albano, 2006). This effect on habitat, when considered in combination with our finding of significantly less wetted bed area ($p = 0.004$), suggests that aquatic habitat may be markedly altered below a diversion. These changes, in addition to the aforementioned increased fine-sediment levels, could negatively influence macroinvertebrate and fish assemblages, contribute to colonization of in-channel macrophytes and periphyton, or allow riparian encroachment (Ligon *et al.*, 1995; Waters, 1995; Rader and Belish, 1999).

Evaluation of fine-sediment measures

The development of multiple areal and volumetric fine-sediment measurement schemes provided greater local-scale

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and reach-wide detail on the shifts in fine sediment than EPA's Environmental Monitoring and Assessment Program (EMAP) protocols, which use a visual estimation of 110 particles (Faustini and Kaufmann, 2007). Each of the five fine-sediment metrics used in this study is characterized by inherent advantages and challenges in definition and application (Table V). For future studies focused on distributions of fine sediment, we would recommend the utility of the areal grid count, for its ability to (1) quickly assess a large area in a limited amount of time, (2) discern the impacts of a range of bed conditions from fines drape to bed armoring and (3) evaluate any substrate size or condition, including bedrock.

Implications for diversion operation and design

Diversion dams are a dominant component of the water-distribution infrastructure in many semiarid lands, yet their operation and design can influence the effect on the downstream ecosystems. In many highly diverted systems, the establishment of environmental flows (often minimum levels) is primarily focused on the larger streams in the system. As demonstrated in this study sample of low-head diversion structures, fine sediment appears to accumulate even when diversion structure configuration undoubtedly passes snowmelt peaks, though gauge data to verify peak flow rated is unavailable. This indicates that multiple elements of the undepleted flow regime may be necessary to sustain important geomorphic and ecological processes (Poff *et al*., 1997). In accordance with Arthington *et al*. (2006), additional effort is needed to evaluate and establish environmental flows on relatively small, biologically rich streams, and such measures should include consideration of passage of moderate- and high-level flushing flows to mitigate fine-sediment deposition. This is especially the case for streams of milder gradient. Beyond flow management, diversion-dam design and construction could also influence the effects on the downstream channel. Structures designed to be submerged or with adjustable gates that would pass a portion of the naturally occurring base and peak flows would allow a more natural hydrograph than backwater structures that homogenize flow by only passing a set volume of water.

Table V. Advantages and challenges of fine-sediment measures

Parameter	Advantages	Challenges
Volumetric % fines—fast	• Allows collective surface and subsurface analysis of fine sediments • If macroinvertebrates are being collected with a sampling cylinder, little additional work is required • Capable of measuring distribution of fines smaller than 2 mm	• Can be difficult to insert cylinder sampler in coarse substrate • Bernoulli effect of flowing water around cylinder can pull fluid and suspended fine sediments from inside of cylinder • Covers minimal area for required effort
Volumetric % fines—slow	• Cylinder sampler tends to seal with bed better in finer substrates • If macroinvertebrates are being collected with a sampling cylinder, little additional work is required • Not subject to skewing due to fines drape • Capable of measuring distribution of fines smaller than 2 mm	• Can be difficult to scoop specific depth of sediments out of cylinder without winnowing • If a large amount of fine sediments are available that will suspend, the fluid within the cylinder needs to be sampled as well • Covers minimal area for required effort
Areal % fines—fast and slow	• Quick visual analysis allowing for a large number of points • Adjustable spatial density sampling depending on sampling grid • Would work on any size or type of sediment, including bedrock • detects influence of fines drape or bed armor	• Quasi-subjective criteria on whether a point is 'fine' or not • Can be confounded by a drape of fines or vegetative matter on the bed • In this study, spatially restricted to areas around cylinder sites • Not capable of determining size distribution of sediment only measures presence /absence of sediment less than 2 mm
Pebble count % fines	• Best spatially distributed sample over the entire reach • Allows full sediment size distribution for all clasts less than 2 mm	• Does not allow for size distribution of fine sediments less than 2 mm • Time consuming and best suited for gravel or cobble bed streams • Accuracy subject to total number of pebbles measured and measurement technique

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CONCLUSIONS

Natural streams are comprised of a heterogeneous mosaic of habitats, created by gradients of hydraulic variation and complex sedimentation patterns. In this study, flow diversion shifted this complex habitat template towards lower flow velocities and more fine sediment. Of the 20-paired observations on 26 reaches, with flow diversion ranging from 23 to 99%, the channels most susceptible to fine-sediment degradation are characterized as having shallow gradients, occurring in small basins, and having smaller-sized coarse substrate. Evidence for increased fine-sediment deposition below diversion dams (particularly for channels of less than 3% slope) was provided by multiple measures of environmental change: a greater prevalence of fine sediment in slow versus fast habitat, a shift towards more slow-flowing zones, and increased levels of fine sedimentation (four of five measures). Findings based on patch-scale areal and surficial measurements are further supported by the increased level of fine sediments within reach-wide pebble counts. In contrast to previous studies with generally inconclusive results regarding downstream effects of diversion dams, the strength of this study stems from careful selection of paired sites with consistent geomorphic setting, the application of multiple measurements of fine-sediment accumulation, and the implementation of a detailed field protocol.

In future studies, streamflow gauging would provide valuable insights into levels of flow diversion over time, the influence of hydrograph characteristics, and episodic flow variation. A laboratory or fully controlled field study allowing controlled manipulation of diversions could provide greater insight into the direct relationships between magnitude of diversion and channel characteristics. Additionally, study of the ability of diversion structures to pass both channel maintenance flows and fine sediment could influence diversion design. The methods used for this project provide as a baseline for future studies of its type, yet further investigation of sediment-sampling techniques is merited to help consider the strengths, limitations and applicability of each.

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