Title

Short-term geomorphic impacts of culvert removal following Best Management Practices in streams of northern California

Author

Lawrence, Justin E

Publication Date

2013

Article; University of California, Berkeley, 2013

Short-term geomorphic impacts of culvert removal following Best Management Practices in streams of northern California

Justin E. Lawrence [1],*, Matthew R. Cover [2], Christine L. May [3], Vincent H. Resh [1]

[1] Department of Environmental Science, Policy, and Management, University of California, Berkeley, 137 Mulford Hall #3114, Berkeley, CA 94720, USA; E-Mails: jlawrence@berkeley.edu (J.E.L.); resh@berkeley.edu (V.H.R.)

[2] Department of Biological Sciences, California State University, Stanislaus, One University Circle, Turlock, CA 95382, USA; E-Mail: mcover@csustan.edu

[3] Department of Biology, James Madison University, MSC 7801, Harrisonburg, VA 22807, USA; E-Mail: maycl@jmu.edu

***** Author to whom correspondence should be addressed; E-Mail: jlawrence@berkeley.edu (J.E.L.); Tel.: +1-510-642-5913; Fax: +1-510-642-7428.

Abstract: Culverts are increasingly removed from road-stream crossings because of their impacts to watersheds. The reconstruction projects often involve installation of open-arch structures and may result in short-term impacts. To evaluate the effectiveness of Best Management Practices (BMPs) for culvert removal of the Klamath National Forest (KNF) of Northern California, we examined the short-term (0-2 years) impacts of culvert removal following KNF BMPs on channel form and sedimentation in six streams in the KNF. Adjustments in channel form and sedimentation were insignificant among the sites examined, but there were notable site-specific effects that may warrant consideration in future stream-crossing reconstruction projects. In conclusion, the BMPs were effective.

Keywords: road-stream crossing; culvert removal; forest roads; sedimentation; mountain streams; channel form; geomorphology; best management practices (BMPs); Klamath

---

1. Introduction

Forest roads and the culverts beneath them can impact watershed hydrology, sediment-transport processes, and stream-channel morphology. For example, these roads can intensify sediment delivery to stream channels through surface erosion and landsliding [1-4]. They can also increase the flashiness of flows by raising hydrologic connectivity [5]. Meanwhile, their associated culverts can lead to formation of plunge pools [6], decay of riffle habitats [7], and accumulation of sediment [8].

In the United States, approximately 700,000 km of paved and unpaved forest roads are located on US Forest Service (USFS) lands [9,10]. Many of these roads were constructed for timber extraction, which peaked on these lands in the 1970s to 1980s. In recent decades, however, a large number of them are infrequently used and not actively maintained [11], resulting in widespread erosion problems and negative impacts to habitat [12-14]. Road-stream crossings on federal forest roads were historically designed to convey 25-year floods, and these designs relied heavily on culverts and did not typically plan for passage of large debris, such as downed trees [15].

Consequently, watershed managers are increasingly replacing culverts with open-arch, road-stream-crossings. These projects are motivated by the perceived value of long-term benefits, which are related to sedimentation, flood-hazard reduction, and fish-passage improvement [16]. However, the short-term geomorphic impacts of these reconstruction projects have not been examined in detail [17].

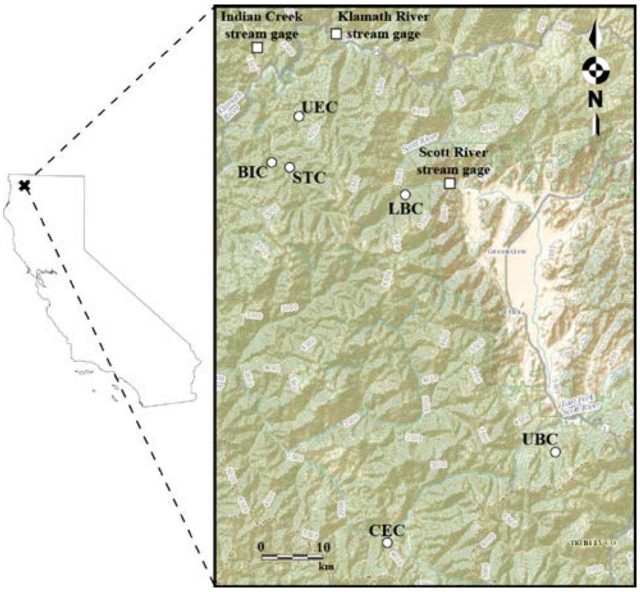
The objective of this study is to evaluate the short-term (0-2 years) impacts of road-stream crossing reconstruction projects following Best Management Practices (BMPs) of the Klamath National Forest (KNF) of Northern California on channel form and sedimentation. We hypothesized that if BMPs of the KNF were ineffective changes in channel form and sediment delivery to channels following culvert removal would be significant among sites. We tested these hypotheses in six stream sites in the KNF.

2. Methods

2.1. Study Location

The KNF is located in the Klamath Mountains, a densely forested region with little human development (Figure 1). Covering an area of about 69,000 km^2, the KNF has a total relief of 2,500 m. The Klamath Mountains are composed of granitic, metamorphic, and volcanic rocks with varying erosion potentials, and the topography is highly dissected [14]. Annual precipitation, which falls as a mixture of rain and snow generally between October and May, ranges from an average of about 250 mm in low elevations to 2,500 mm at high elevations [15]. Winter storms can trigger landslides and debris flows that can deliver large pulses of sediment to streams [18] that can fill or overload culverts.

Figure 1. Location of the six study sites (codes defined in Table 1), three stream gages, local towns, main roads, and primary streams in the Klamath National Forest (KNF), Northern California.



Six streams in the KNF that were prioritized by the USFS for road-stream-crossing reconstruction were selected for study; throughout the paper, specific sites are identified by a three letter code (Table 1). The USFS prioritized these sites both because of their potential as fish migration barriers and also their risk of catastrophic failure during high-flow events or debris flows, as suggested by a stream blocking index [19]. The lithology underlying the sites includes rocks with high erosion potential, such as sandstones, slaty mudstones, siltstones, and shales [12]. The sites all contained steel-pipe culverts ranging from 2.1 m to 3.7 m in diameter and 13 m to 31 m in length that were replaced with open-arched structures (Table 1, Figure 2). Prior to reconstruction, the drop from the downstream end of the culverts to the streambed ranged in height from 1.0 m to 2.8 m (Table 1).

Table 1. Site information and description of activities.

Creek Name	Bishop Creek	Cecil Creek	Lower Boulder Creek	Stanza Creek	Upper Boulder Creek	Upper Elk Creek
Site Abbreviation	BIC	CEC	LBC	STC	UBC	UEC
Reconstruction Completion	10/16/2004	8/3/2004	10/10/2005	8/31/2005	10/1/2004	10/21/2004
Latitude, Longitude	41° 40' 15.873", -123° 21' 13.2624"	41° 7' 33.3978", -123° 7' 59.6784"	41° 37' 29.2188", -123° 5' 57.8184"	41° 39' 49.698", -123° 19' 10.0632"	41° 15' 21.7584", -122° 48' 41.3202"	41° 44' 13.3362", -123° 18' 6.7572"
Drainage Area (km^2)	7.3	9.7	10.7	5.0	0.7	12.1
Elevation (m ASL)	641	782	908	692	1476	595
Ave. Bankfull Width (m)	5.0	5.9	6.3	3.6	7.8	5.8
Ave. D_{50} (mm)	68	279	215	46	131	89
Date Sediment Traps Installed, Removed	8/4/2004, 11/15/2004	7/28/2004 , 8/24/2004	7/6/2005, 11/1/2005	6/23/2005, 10/25/2005	8/19/2004, 11/3/2004	7/14/2004, 11/9/2004
Potential Migration Barrier (m)	1.5	1.5	2.8	1	1.5	1.5
Fill Volume Removed (m^3), % Removed	1707, 72%	28, 4%	772, 69%	4485, 91%	629, 31%	4378, 99%
Culvert height (m), width (m), slope (%), length (m)	3.7, 3.7, 5, 26	2.4, 3.5, 8, 13	3.7, 3.0, 10, 31	2.1,2.1, 6.5, 31	2.4, 2.1, 7, 13.6	2.8, 4.4, 3.5, 14.9
Overall Channel Slope (%) in Y0-pre, Y0-post, Y1, and Y2	5.6, 5.7, 5.5, 5.7	6.4, 6.4, 6.5, 6.4	11.8, 12, 11.7, 11.8	7.5, 7.5, 7.5, 7.5	10.8, 10.8, 10.8, 10.9, 10.8	5.3, 5.4, 5.3, 5.3
Channel Slope Upstream of Culvert in Y0-pre, Y0-post, Y1, and Y2	4.6, 4.8, 5.1, 5.7	6.5, 6.7, 6.9, 7.0	9.3, 9.0, 10.7, 10.7	6.9, 7.0, 6.7, 6.9	10.0,10.7, 10.1, 10.3	10.7, 9.8, 11, 11
Channel Slope Downstream of Culvert in Y0-pre, Y0-post, Y1, and Y2	5.9, 6.0, 6.2, 5.7	8.6, 8.7, 8.5, 9.2	11.7, 11.7, 12.1, 12.3	8.6, 8.7, 8.5, 9.2	10.7, 9.8, 11, 11	5.4, 5.0, 5.3, 5.2
Open-Arch Structure height (m), width (m), slope (%), length (m)	3.3, 5.7, 7.0, 16	2.8, 7.1, N/A, 7.9	4.3, 10.4, 7.0, 8.2	3.5, 5.2, 9.0, 18	3.8, 7.2, 13, 13	3.9, 8.5, 7, 7.9

Figure 2. An example of before (A) and after (B) road-stream-crossing reconstruction from STC.

Three stream gages in the region that are operated by the US Geological Survey provide information relevant to the high flow events that occurred during the study and that may have resulted in bed mobilization and sediment transport (Figure 1). The Indian Creek gage is likely the most representative of the hydrology at the study sites because it is located on the smallest stream (DA = 311 km^2), although it is still large relative to the study sites (average DA = 7.6 km^2). In steep, cobble- and boulder-dominated, step-pool streams with occasional riffles, rapids, and cascades, similar to those in the study, finer grained sediment stored in pools is mobilized near bankfull discharges, while the larger, cobble- and boulder-classes that make up the steps are mobilized much less frequently, i.e., >10 years [20-21]. During the study period, discharges at Indian Creek exceeded bankfull in water years 2005, 2006, and 2007. The 2006 flood was the largest that occurred during this period, with an 11 year return period; it was approximately 4x the magnitude of a bankfull event. This same flood had a return period of 11 years at the Scott River, based on 67 years of records, and 14 years at the Klamath River, based on 70 years of records. The flow regime of the Klamath River is influenced by upstream dams.

2.2. Overview of Study Design

We assessed changes in channel form and streambed sediment by conducting surveys before (Y0-pre), several weeks after (Y0-post), one year after (Y1), and two years after (Y2) culvert removal and road-stream-crossing reconstruction. To assess the magnitude of sediment deposition resulting from the reconstruction project, we measured the mass of fine sediment that was deposited in sediment traps, which were deployed for the 1-4 month construction period (Y0-pre to Y0-post). Crossings at all six streams were originally scheduled to be reconstructed during 2004, but as a result of construction delays only four culverts were replaced in 2004 and the remaining two were not replaced until the following year. Because each stream was monitored from Y0 to Y2 regardless of which year its construction began, the field-sampling effort was conducted over a four year period (2004-2007).

2.3 Channel Form

We surveyed both longitudinal thalweg profiles and cross-sections of stream channels at each site using an automated level. Seven channel cross-sections were surveyed upstream (XU1-XU7) and five downstream (XD1-XD5) of each road-stream-crossing. All cross sections were spaced approximately four bankfull widths apart. The cross sections nearest the road-stream-crossing were located 2 m from the upstream (XU1) and downstream (XD1) ends of the culvert. Longitudinal profiles extended from

20 m above (i.e., upstream of) the furthest upstream cross-section (XU7) to 20 m below the furthest downstream cross-section (XD5). The total lengths of the longitudinal profiles ranged from 77-153 m.

We extended cross-section surveys onto adjacent floodplain terraces to capture breaks in the slope beyond the edges of the bankfull channel. We spaced survey points no more than 0.5 m apart in the bankfull channel and no more than 1.0 m apart on the floodplain. Bankfull widths were identified at each cross-section based on geomorphological evidence of erosion and deposition, as well as recent vegetation growth, within the past 1.5-2 years [*sensu* 22]. We monumented all cross sections on both ends with rebar stakes. These stakes remained in place throughout the study except for those at XU1 and XD1, which were removed by necessity at all the sites to complete the construction activities.

We also measured the total number and average depth of pools upstream and downstream of road-stream-crossings in our survey reaches. We defined pools as channel features with a maximum low-flow depth >0.5 m; this criteria was selected based on field evidence as the minimum water depth needed to allow consistent hydraulic functioning as a pool (i.e., relatively slow surface velocity) in these fast-flowing headwater streams, which typically exhibit step-pool or cascade morphology [23].

We conducted surveys prior to construction activities (Y0-pre) to quantify the dimensions and slope of the culverts and the amount of road fill, which can be used in the future as a baseline to assess benefits of the projects, such as improved fish passage and reduced risk of catastrophic failure [24]. We measured the difference in elevation between the base of the culvert at the downstream outlet and the streambed in the plunge pool. This difference in elevation was assumed to be the maximum height of the potential migration barrier below the culvert. We calculated the amount of fill that was removed during construction by subtracting the volume of fill surrounding the new open-arch structures (based on design plans prepared for the project) from the volume of fill surrounding the original culvert. This difference in fill volume was used as a measure of risk reduction in terms of sediment delivery to the stream that could result following a failure of the road-stream-crossing during a flood or debris flow.

2.4 Sediment

To assess changes in streambed sediment resulting from the reconstruction projects, we quantitatively characterized three aspects: (1) the proportion of fine sediment on the streambed surface, which we refer to as bed-surface fine-sediment; (2) bed-surface grain-size distributions; and (3) fine sediment deposited in sediment traps, which were deliberately installed in pools and channel margins.

Presence or absence of bed-surface fine-sediment (< 4 mm) was recorded at the tip of a steel pin placed at grid intersections on a 2.7 m x 1.2 m net with a 13 cm grid-spacing, for a total of 210 points per net [25]. One transect was measured along the upstream edge and another along the downstream edge of each cross section. The sampling domain for the bed-surface fine-sediment was limited to the wetted channel, excluding major slack-water pockets and islands of exposed substrate that were permanently vegetated. Thus, the total number of sample points on each cross section was 420 points, while the total number of points per reach (5-7 cross-sections) ranged from 2,100 to 2,940 points.

We measured bed-surface grain-size distributions using pebble counts [26], which consisted of a minimum of 100 grains per cross section. Particles were measured every 0.3 m along diagonal transects in the wetted channel. A total of 305 to 510 particles were sampled per reach.

We constructed sediment traps from plastic bowls 17 cm diameter and 8 cm deep; we drilled eight equally spaced 0.64 cm holes into the side of each bowl 1 cm below the rim to allow lateral infiltration of fines [similar to 27]. Traps were filled to the rim with sieved, clean bed material 20-30 mm in diameter. We installed five traps in each upstream study reach between XU4 and the top of the reach (20 meters above XU7), and five traps in each downstream study reach between XD3 and the bottom of the reach (20 meters below XD5). Prior to construction (Y0-pre), and during summer low flow conditions (June-August), traps were buried in the streambed so that rims were flush with the bed surface. Sediment traps were placed in locations believed to be depositional habitats (i.e., pools and margins) under base-flow conditions; however, it was impossible to control for the degree of depositional environments (i.e., some streams may have had conditions that favored greater deposition than others). Traps remained in place for the duration of construction activities, and were removed about one month after reconstruction was complete, and prior to the onset of large winter storms; most traps were deployed for 3-4 months (Table 1). Some very light rainfall may have occurred during the deployment period, as suggested by small spikes in the hydrograph at the Indian Creek gage, but these flows were not large enough to cause bed mobility in our study streams. Thus, fine sediment that collected in the traps resulted from deposition of suspended sediment supplied from localized inputs.

During the retrieval of the sediment traps, the original (20-30 mm) gravel pieces that were installed in the traps to serve as representative preconstruction streambed material were separated from the accumulated debris by washing the gravel particles with a pressurized spray of water. Particulate organic-matter was removed from the sediment samples using a series of hydrogen peroxide baths (30% solution) that continued until further additions of hydrogen peroxide failed to produce a reaction. The remaining inorganic sediment was wet sieved into seven grain-size classes ranging from 0.063 mm to 4 mm, dried in a muffle oven, and subsequently weighed to the nearest hundredth of a gram.

2.5 Data Analysis

We plotted longitudinal profiles and cross sections to examine differences both over time (Y0-pre, Y0-post, Y1, Y2) and between upstream and downstream reaches. To account for possible, reach-wide changes in longitudinal-thalweg profiles, we calculated reach slopes from linear-regression trend-lines. We examined changes in thalweg elevation and cross-sectional area of the monumented upstream and downstream cross sections to assess the occurrence of bed and bank erosion and channel widening.

Formal statistical tests were performed to compare various measures of streambed sediment with time and between upstream and downstream reaches. We avoided pseudoreplication in the among-site comparisons by combining the upstream and downstream data into two groups and treating sites rather than individual samples as replicates. Prior to running the statistics, we tested the distributions for normality and equality of variance to inform our choice between a parametric and nonparametric test.

Consequently, changes in bed-surface fine-sediment between all combinations of years were determined by computing the percent bed-surface fine-sediment upstream and downstream and performing a non-parametric ANOVA on ranks. Differences in the volume of fine sediment deposited in sediment traps between upstream and downstream reaches were assessed using a parametric t-test paired by stream. To explore sedimentation effects at the site-specific level, differences between upstream and downstream samples in specific grain-size classes were evaluated using either a t-test (if parametric assumptions were met) or a Mann-Whitney Rank-Sum test (if assumptions were not met).

We calculated the total volume of sediment eroded or aggraded between Y0-pre and Y2 using the double-end area method [28], which integrates changes in sediment storage between cross-sections. We examined correlations among changes in sediment volume ($\log_{10}$-transformed) and fine sediment deposited in the traps, channel gradient, median grain size, and removed fill-volume to elucidate possible mechanistic relationships between changes in channel form and other physical factors.

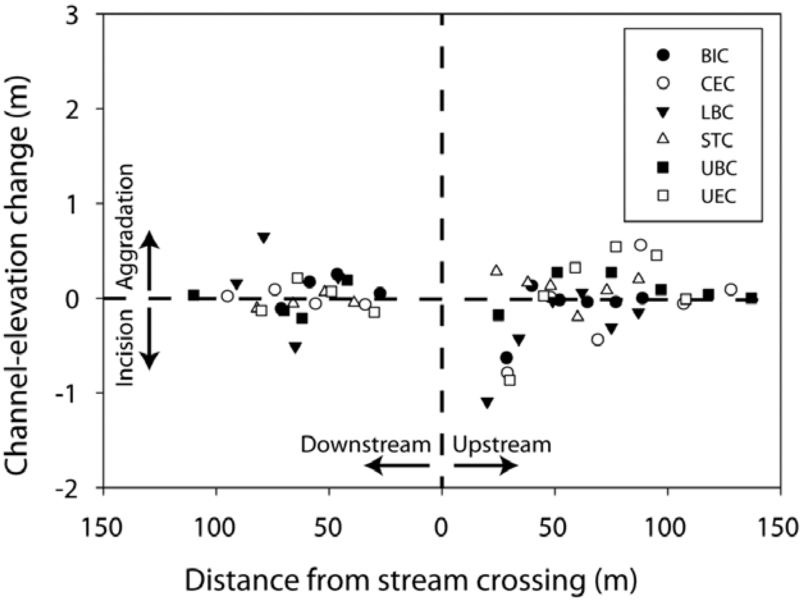
3. Results

3.1 Channel Form

Following culvert removal, some stream channels incised into alluvium that had accumulated upstream of the road-stream crossings and aggraded downstream. This resulted in more uniform channel slopes between the upstream and downstream reaches. At BIC, for example, the preconstruction slope of the upstream reach was < the downstream reach (4.6% upstream vs. 5.9% downstream), but by Y2 both reaches had slopes of 5.7% (Table 1). The largest difference in slope between the upstream and downstream reaches prior to construction was at LBC (9.3% vs. 11.7%), but by Y2 this difference was reduced by >30% as a result of steepening in the upstream reach (Table 1).

At sites where a relatively large amount of fill material was removed (e.g., UEC and STC; Table 1), localized aggradation occurred, primarily in the upstream reach. For example, at UEC aggradation occurred in five of the six monumented cross-sections upstream and in only two of the four downstream (Figure 3). Similarly, at STC aggradation occurred at five of six of the cross-sections upstream, but at only one downstream. In contrast, CEC had more pronounced incision and aggradation at upstream sites relative to downstream sites.

Figure 3. Incision or aggradation that occurred from Y0-pre to Y2 at cross-sections upstream and downstream of the road-stream crossings, calculated using elevation changes observed in the thalweg.



Between Y0-pre and Y2, cross-sectional areas at XU2 increased up to 17 m^2 ($\bar{X}$ = 8 m^2) (Table 2). Moreover, increases in cross-sectional areas observed from Y0-pre to Y1 ($\bar{X}$ = 9.6 m^2) were larger than those from Y1 to Y2 ($\bar{X}$ = 1.8 m^2) (Table 2). UBC was the most stable of the sites, with minimal incision (0.01 m), and no notable increase from Y0-pre to Y2 in cross-sectional area at XU2 (Table 2).

Table 2. Cross-sectional areas of the monumented upstream (XU7-XU2) and downstream (XD2-XD5) cross-sections. Two different values separated by '/' in the Y0 row indicate information for Y0-pre and Y0-post. When only one value is present, it indicates information for Y0-pre. The changes (positive or negative) from Y0-pre are indicated with arrows (up or down, respectively).

Site	Study Period	XU7 (m^2)	XU6 (m^2)	XU5 (m^2)	XU4 (m^2)	XU3 (m^2)	XU2 (m^2)	XD2 (m^2)	XD3 (m^2)	XD4 (m^2)	XD5 (m^2)
BIC	Y0	4	13	6	10	6	27 / 39	15	32	41	47
	Y1	5 ↑	13	6	10	16 ↑	38 ↑	16 ↑	31 ↓	40 ↓	47
	Y2	4	14 ↑	7 ↑	10	12 ↑	41 ↑	16 ↑	30 ↓	40 ↓	49 ↑
CEC	Y0	32	34	20	8	15	12	12	3	18	10
	Y1	35 ↑	36 ↑	22 ↑	8	15	13 ↑	13 ↑	3	17	12 ↑
	Y2	34 ↑	34	17 ↓	10 ↑	14 ↓	15 ↑	12	4 ↑	16 ↓	13 ↑
LBC	Y0	11	10	25	22	18	23 / 37	11	16	13	15
	Y1	11	11 ↑	27 ↑	23 ↑	20 ↑	42 ↑	12 ↑	19 ↑	8 ↓	17 ↑
	Y2	10 ↓	10	26 ↑	21 ↓	20 ↑	40 ↑	11	19 ↑	10 ↓	19 ↑
STC	Y0	10	7	14	15	8	10	22	19	23	10
	Y1	10	8 ↑	16 ↑	13 ↓	7 ↓	9 ↓	24 ↑	18 ↓	22 ↓	10
	Y2	8 ↓	7	15 ↑	14 ↓	7 ↓	9 ↓	23 ↑	19	24 ↑	11 ↑
UBC	Y0	16	17	12	26	69	35	19	7	18	7
	Y1	16	15 ↓	7	21 ↓	65 ↓	34 ↓	20 ↑	7	18	8 ↑
	Y2	16	16 ↓	7	23 ↓	64 ↓	34 ↓	17 ↓	7	17 ↓	7 ↓
UEC	Y0	13	16	17	10	21	36 / 49	8	15	15	6
	Y1	13	13 ↓	17	9 ↓	20 ↓	51 ↑	8	15	15	7 ↑
	Y2	12 ↓	11 ↓	15 ↓	8 ↓	20 ↓	52 ↑	9 ↑	14 ↓	15	7 ↑

Both the total number of pools along the study reaches and the maximum depth of the plunge pools below the road-stream crossings decreased following road-stream crossing reconstruction. For example, our study sites had 3 to 12 ($\bar{X}$ = 6) pools in Y0-pre, but only 0 to 6 ($\bar{X}$ = 4) pools in Y2 (Table 3). The depth of the first pool downstream of the crossings ranged from 0.8 to 1.5 m ($\bar{X}$ = 1.1 m) in Y0-pre, and from 0.5 to 0.7 m ($\bar{X}$ = 0.6 m) in Y2. The largest preconstruction plunge pool was 1.5 m deep at LBC. It was reduced in depth to 0.51 m following reconstruction of the road-stream crossing.

Table 3. Pools upstream (top number) and downstream (bottom number) of the road-stream crossings in Y0-pre, Y0-post, Y1, and Y2. "–" indicates no pool.

Site	Reach Length (m)	Y0-pre			Y0-post			Y1			Y2		
		# of Pools	Ave. Depth (m)	Plunge Pool Depth (m)	# of Pools	Ave. Depth (m)	Plunge Pool Depth (m)	# of Pools	Ave. Depth (m)	Plunge Pool Depth (m)	# of Pools	Ave. Depth (m)	Plunge Pool Depth (m)
BIC	94	1	0.80	--	--	--	--	--	--	--	--	--	--
	79	2	0.83	1.20	2	0.87	0.68	1	0.74	0.91	1	0.71	0.71
CEC	143	2	0.69	--	1	0.54	--	1	0.54	--	4	0.57	--
	102	3	0.70	1.23	1	0.78	0.88	1	0.54	0.54	--	--	--
LBC	118	7	0.66	--	8	0.58	--	5	0.69	--	4	0.57	--
	87	5	0.66	1.50	1	0.51	0.51	4	0.59	0.51	2	0.59	0.51
STC	98	2	0.61	--	1	0.55	--	2	0.74	--	--	--	--
	77	1	0.64	0.76	1	0.68	0.68	--	--	--	--	--	--
UBC	153	6	0.64	--	4	0.59	--	2	0.62	--	2	0.64	--
	113	2	0.65	0.96	6	0.58	0.51	3	0.60	0.60	4	0.61	0.53
UEC	119	4	0.67	--	2	0.69	--	2	0.65	--	3	0.60	--
	88	2	0.84	1.07	1	0.65	0.65	1	0.59	0.61	3	0.61	0.53

3.2 Sediment

Bed-surface fine-sediment was not significantly different between upstream ($\bar{X}$ = 13%) and downstream ($\bar{X}$ = 14%) reaches among years (Prob>F = 0.30), based on the grid sampling. However, there was some evidence for increased levels of fine sediment following reconstruction at half of the sites. Fine sediment in the downstream reach of UEC increased from 8% to 24% between Y0-pre and Y1. At STC, the difference in fine sediment between upstream and downstream reaches was negligible prior to reconstruction (26% upstream vs. 27% downstream), but much higher in the downstream reach in both Y1 (9% vs. 18%) and Y2 (16% vs. 29%). Similarly, the difference between upstream and downstream reaches at BIC was also negligible prior to reconstruction (11% upstream vs. 11% downstream), but higher in the downstream reach in Y1 (7% vs. 17%). No evidence suggested increased deposition of bed-surface fine-sediment following reconstruction at the remaining three sites.

The greatest changes in bed-surface fine-sediment observed among the sites occurred following a large flood in the winter of 2006. This flood reduced fine sediment in the downstream reach in four out of six streams; the same effect also occurred upstream in four of the six streams. For example, following a large increase in fine sediment observed in the downstream reach at UEC after reconstruction, fine-sediment levels reduced to nearly preconstruction levels after the 2006 flood.

No significant difference was evident in the D_{50}, D_{16}, or D_{84} between upstream and downstream reaches following the reconstructions (P = 0.65, 0.24, and 0.57, respectively) (Table 4). In Y0-pre, the difference in D_{50} between the upstream and downstream reaches averaged 38 mm; only one site (CEC) had a difference >50 mm. The average D_{16} over all sites and years was the same upstream ($\bar{X}$ = 5 mm) and downstream ($\bar{X}$ = 5 mm), and the average D_{84} was nearly the same ($\bar{X}$ = 443 mm vs. $\bar{X}$ = 447 mm). The large 2006 flood did not appear to have a notable impact on any of the grain-size distributions.

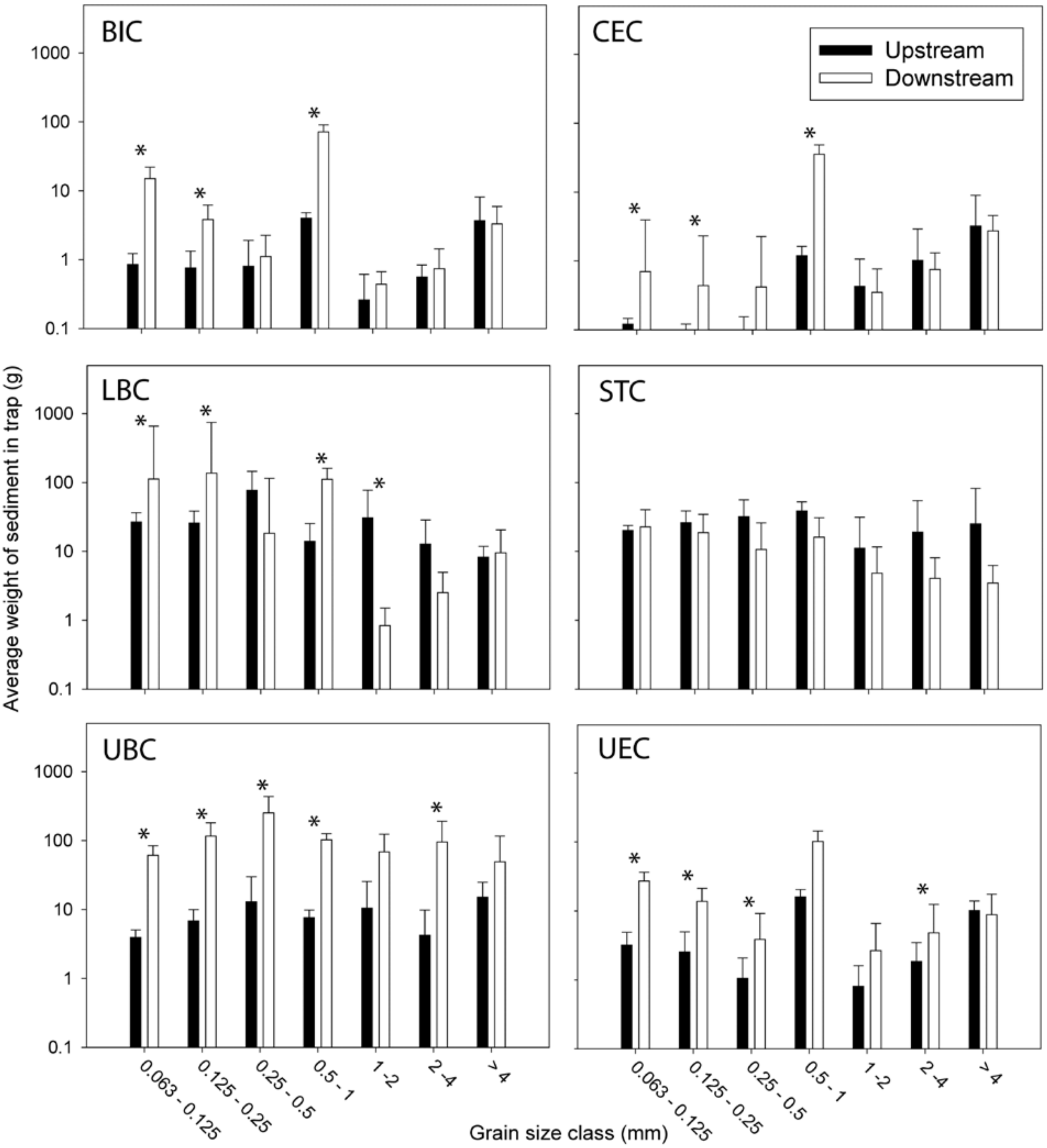
Table 4. Summary statistics of pebble counts upstream and downstream of the stream crossings in Y0-pre, Y1, and Y2.

Treatment	Site	D_{16} (mm)			D_{50} (mm)			D_{84} (mm)		
		Y0-pre	Y1	Y2	Y0-pre	Y1	Y2	Y0-pre	Y1	Y2
Upstream	BIC	8	6	5	67	82	64	313	442	365
	CEC	6	4	4	128	113	134	460	385	476
	LBC	<4	5	4	123	252	157	498	585	520
	STC	<4	<4	<4	50	69	61	354	299	407
	UBC	5	<4	5	186	145	237	516	445	623
	UEC	4	4	5	91	66	90	457	371	464
Downstream	BIC	8	<4	4	58	53	59	273	428	257
	CEC	6	5	7	257	445	264	550	607	607
	LBC	<4	5	<4	104	178	114	370	459	478
	STC	<4	<4	<4	70	23	91	397	421	439
	UBC	<4	4	4	164	117	166	554	408	542
	UEC	5	4	6	118	112	84	439	425	386

The average amount of fine sediment deposited in sediment traps was three times greater in downstream reaches ($\bar{X}$ = 253 g, SD = 271 g) than in upstream reaches ($\bar{X}$ = 80 g, SD = 83 g). This difference was not statistically significant, however, because of the large variability among sites (P = 0.17, Figure 4). There was over an order of magnitude difference between the site with the most (UBC, 805 g) and the least (CEC, 46 g) fine-sediment deposition in sediment traps. The average amount of fine sediment deposited in the first traps downstream of crossings ($\bar{X}$ = 326 g, SD = 428) was over twice as great as in the furthest downstream traps ($\bar{X}$ = 136 g, SD = 209; P=0.31). The furthest downstream traps also had greater sediment accumulation than the upstream traps (P = 0.55).

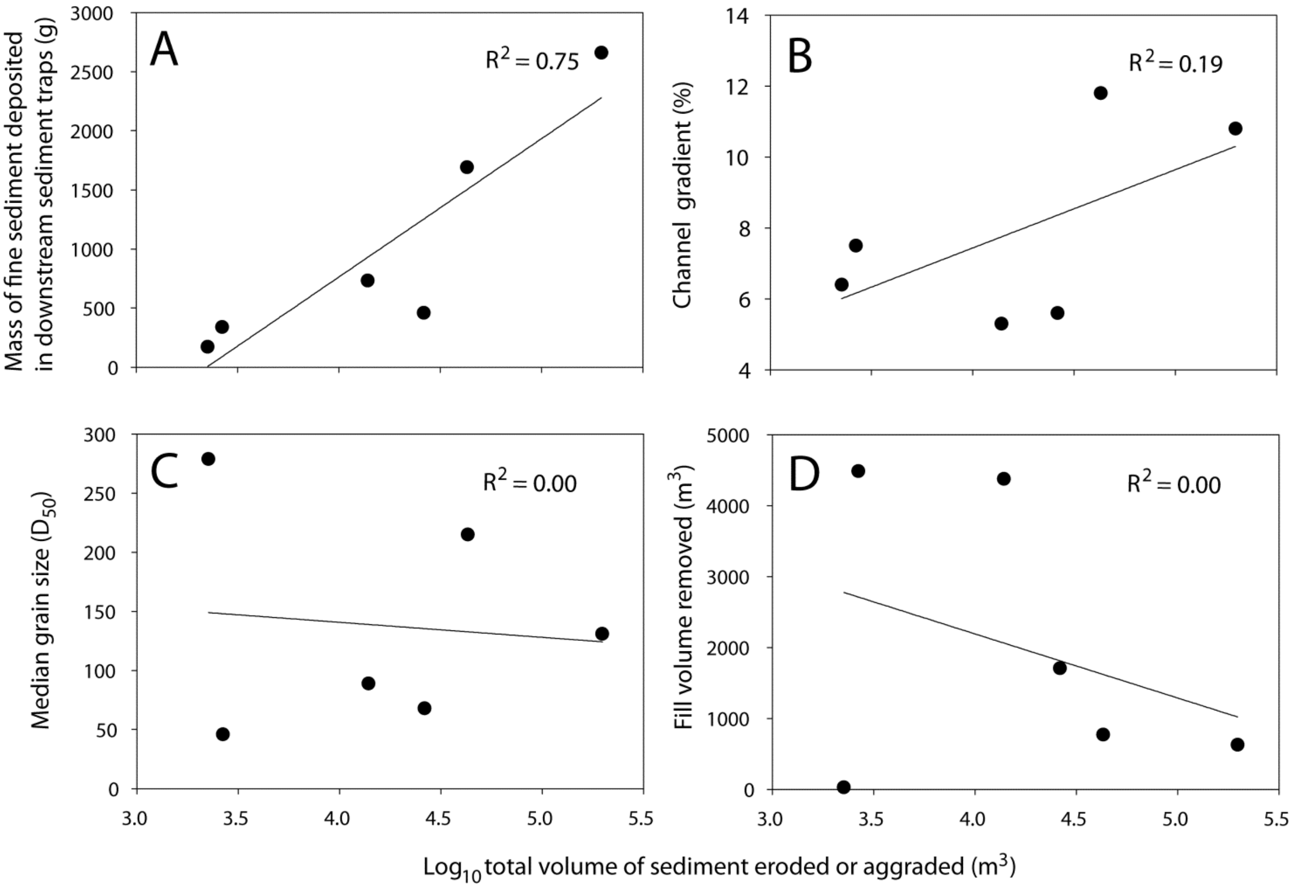
The total amount of fine sediment deposited in the <0.5 mm size fractions was more pronounced downstream than upstream at many sites, but it was still insignificant among the sites (P = 0.21). However, there were notable site-specific effects at five of the six sites, including differences in all of the grain-size classes <4 mm at one or more sites (Figure 4). Five of six sites accumulated notable amounts of very fine sand to fine sand (0.063-0.25 mm) in downstream reaches (Figure 4).

Figure 4. The amount of sediment deposited in the traps grouped by sediment grain-size class. The tails on the bars indicate standard deviation. * indicates a notable (P<0.05) site-specific difference between upstream and downstream sediment samples. No Bonferroni adjustment was applied because these comparisons are exploratory; among the sites these comparisons were insignificant.



The total volume of sediment eroded or aggraded between Y0-pre and Y2 correlated with the amount of medium and fine sand deposited in downstream traps (R^2=0.75; Figure 5). The greatest change in sediment storage occurred at the two sites with the steepest channels (i.e., LBC and UBC), whereas the sediment storage was not correlated with streambed grain size or the volume of fill removed (Figure 5; R^2=0.00).

Figure 5. Erosion or aggradation observed along the entire reach (calculated using the double-end area method between cross-section area measurements) in relation to: (A) fine sediment in the 0.063-0.5 mm diameter size range deposited in sediment traps downstream of the road-stream crossings; (B) channel gradient; (C) median grain size; and (D) the volume of fill removed.



4. Discussion

Forest roads can impact the geomorphology of streams in mountainous landscapes [11]. For example, road-stream crossings can fail completely, resulting in large sediment pulses that initiate debris flows and force changes in channel form [18,29-31]. Road-stream crossings along forest roads on USFS property are reconstructed following Best Management Practices (BMPs). In this study, we did not observe significant changes in channel form or sedimentation. However, if we had had the resources to include a larger population of study sites the results may have shown significance.

The site-specific geomorphic responses to the reconstructions were a result of culverts acting as grade-controls. Following culvert removal, some channels re-established their natural grade by eroding sediment that had accumulated upstream of crossings, as observed in other studies [8,32]. At sites where a relatively large amount of fill was removed (i.e., UEC and STC), aggradation occurred. We also observed loss of plunge pools downstream of crossings, as well as a decline in the total number of pools in the sites. These processes were influenced by climate, occurring more rapidly in wet years (e.g., during the 2006 flood, which was a large magnitude event of a 10-20 year return interval).

We did not observe a systematic increase in bed-surface fine-sediment upstream or downstream, which is not surprising because streams in the KNF are relatively steep in relation to their drainage areas and have a relatively high sediment-transport capacity compared to other mountain streams [18,33]. Previous research in the KNF found that the high transport capacity of these streams may limit the accumulation of fine sediment in riffles and rapids to the wake zones of boulders [25]. Thus, any increase in fine-sediment from the culvert removal would likely have been flushed out of the fast-water habitats after high flows. The site-specific decreases in fine sediment on the bed surface downstream of the culverts at many of our sites following the large 2006 flood event demonstrates the high transport capacity of these channels. This finding is in agreement with other studies that have shown steep, alluvial mountain channels to have both high ratios of transport capacity to sediment supply and resilience to changes in stream flow and sediment availability [21].

Although much of the sediment introduced into the streams was likely carried great distances (i.e., longer than our longitudinal profiles), the site-specific effects observed suggest that a notable portion of the fine sediment was likely flushed through riffles and rapids and deposited locally in pools and channel margins. This deposition was more pronounced in sediment traps in downstream reaches at sites that experienced large changes in upstream channel form. Additionally, sediment deposition in traps was greatest just downstream of road-stream crossings and decreased in a downstream direction. The distance for downstream sedimentation effects to dissipate was not measured, but other studies in Northern California have found it to be about 400 meters [34]. This distance, however, is likely to strongly depend on local environmental factors, such as channel gradient, sediment size, and lithology.

The 0-2 year time period following road-stream-crossing reconstruction has been identified as the most significant period for sediment movement in streams following human disturbance [35]. In a similar culvert study conducted in Northern California, Maurin and Stubblefield [36] observed that erosion and aggradation were most significant in the first year following reconstruction and they suggest that streams should be excavated to bedrock or coarse material after culvert removal. Similarly, we also observed channel stabilization in the first year following reconstruction, which was evidenced by the smaller changes in channel form that occurred in the later period Y1 to Y2 compared to the earlier period Y0-pre to Y1. A visual inspection of all sites in 2009 (4-5 years after construction) revealed no notable changes in morphology since the last surveys were conducted in 2006 or 2007.

The outcome of road-stream-crossing reconstruction has varied among studies, with impacts extending different distances downstream depending on local geomorphic and climatic conditions. A study in the Northern California Coast Range conducted by Harris et al. [37] reported minimal channel erosion associated with road-stream-crossing reconstruction at most of the sites evaluated. This suggests that the BMPs applied there were successful. Brown [38] and Foltz et al. [39] observed mildly elevated turbidity and suspended sediment downstream of culvert removal projects in Washington and Idaho, whereas no impacts were observed 810 m downstream. Brock et al. [34] reported that construction activities increased fine sediment for a large road-stream-crossing reconstruction project in the Shasta-Trinity National Forest, but they did not observe any impacts 4.8 km downstream.

5. Conclusions

The BMPs were successful. Although the impacts were insignificant among sites, there were notable site-specific effects that may warrant consideration in future reconstruction projects. Several channels experienced incision, aggradation, and/or widening as channels re-established a more uniform grade. Managers could minimize geomorphic responses by completely removing grade-controls and re-establishing uniform channel slopes. A fluvial geomorphologist or hydrologist could assess the sites prior to completion to insure that a relatively stable channel form is re-established. Additionally, we observed notable sedimentation in depositional areas downstream during and/or immediately following reconstruction at a number of sites. Although the source and exact timing of this sediment deposition is unknown, the fact that the greatest accumulation occurred in channels that exhibited larger geomorphic responses suggests that much of this accumulation originated after construction was complete when water was allowed to flow over the reconstructed channel. Thus, ensuring that channels have a relatively uniform slope through the project area should also help to reduce subsequent downstream sediment deposition. Other issues we identified (but did not quantify) that could have caused localized problems and differences among the sites included difficulty in fully dewatering some sites during construction, and different interpretations of BMP guidelines by different construction contractors.

Acknowledgments

This study was funded by the USFS Region 5 and the KNF under Cost Share Agreement #03-CR-11052007–042. We thank B. Staab, B. Hill, J. Furnish, and J. de la Fuente as project managers; D. Elder, R. Quionones, and S. Renner as USFS field liaisons; S. Mauer as field manager; S. Addison, S. Campbell, W. Beaver, J. Bowman, A. Kistler, R. Knight, P. Lauer, B. Silva, S. Simpson, S. Stenhouse, T. Sullivan, S. Unger, J. Warner, and M. Whitman as field crew members; B. Dietrich, S. Hilton, and T. Lisle as collaborators on the study plan and methods; M. Matella for assistance with calculations in ArcGIS; J. de la Fuente, D. Elder, and E. Rose for their insightful comments on earlier drafts.

References

1. Reid, L.M.; Dunne, T. Sediment production from forest road surfaces. *Water Resour. Res.* **1984**, 20, 1753-1761.
2. Switalski, T.A.; Bissonette, J.A.; DeLuca, T.H.; Luce, C.H.; Madej, M.A. Benefits and impacts of road removal. *Front. Ecol. Environ.* **2004**, 2, 21-28.
3. Montgomery, D.R. Road surface drainage, channel initiation, and slope instability. *Water Resour. Res.* **1994**, 30, 1925-1932.
4. Madej, M.A.; Eschenbach, E.A.; Diaz C.; Teasley R.; Baker, K. Optimization strategies for sediment reduction practices on roads in steep, forested terrain. *Earth Surf. Proc. Land.* **2006**, 31, 1643-1656.
5. Wemple, B.C.; Jones, J.A.; Grant G.E. Channel network extension by logging roads in two basins, Western Cascades, Oregon. *Water Resour. Bull.* **1996**, 32, 1195-1207.
6. Khan, B.; Colbo, M.H. The impact of physical disturbance on stream communities: Lessons from road culverts. *Hydrobiologia* **2008**, 600, 229-235.
7. Merrill, M.A. The effects of culverts and bridges on stream geomorphology. M.Sc. thesis, Department of Natural Resources, North Carolina State University, Raleigh, N.C. **2005**.

8. Jackson, S.D. Ecological considerations in the design of river and stream crossings. In Proceedings of the 2003 International Conference on Ecology and Transportation, Raleigh, NC, USA, 2003; Irwin, C.L., P. Garrett, P., McDermott, K.P., Eds.; Center for Transportation and the Environment, North Carolina State University, Raleigh, NC, USA.
9. Madej, M.A. Erosion and sediment delivery following removal of forest roads. *Earth Surf. Proc. Land.* **2001**, 26, 175–190
10. Elseroad, A.C.; Fulé, P.Z.; Covington W.W. Forest road revegetation: effects of seeding and soil amendments. *Ecol. Restor.* **2003**, 21, 180-185.
11. U.S. Department of Agriculture Forest Service (USFS). Forest roads: a synthesis of scientific information. General Technical Report PNW-GTR-509. Pacific Northwest Research Station. Portland, OR, USA, 2001. 103 p.
12. Amaranthus, M.P.; Rice, R.M.; Barr, N.R.; Ziemer, R.R. Logging and forest roads related to increased debris slides in southwestern Oregon. *J. Forest.* **1985**, 83, 229-233.
13. Furniss, M.J.; Ledwith, T.S.; Love, M.A.; McFadin, B.C.; Flanagan, S.A. Response of road-stream crossings to large flood events in Washington, Oregon, and Northern California. USDA Forest Service. Technology and Development Program. 9877-1806-SDTDC, 1998. 14 p.
14. Cafferata, P.H.; Coe, D.B.R.; Harris, R.R. Water resource issues and solutions for forest roads in California. *Hydrol. Sci. Tech.* **2007**, 23, 39-56.
15. U.S. Department of Agriculture Forest Service (USFS). Cumulative watershed effects from three models applied to 249 seventh-field watersheds on the west side of the Klamath National Forest: Don Elder (author), unpublished. USDA Forest Service, Klamath National Forest, Yreka, CA, USA, 1998.
16. Ice, G. History of innovative Best Management Practice development and its role in addressing water quality limited waterbodies. *J. Environ. Eng.-ASCE* **2004**, 130, 684-689.
17. Luce, C.H.; Wemple, B.C. Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surf. Proc. Land.* **2001**, 26, 111-113.
18. Cover, M.R.; de la Fuente, J.; Resh, V.H. Catastrophic disturbances in headwater streams: the long-term ecological effects of debris flows and debris floods in the Klamath Mountains, northern California. *Can. J. Fish. Aquat. Sci.* **2010**, 67, 1596-1610.
19. U.S. Department of Agriculture Forest Service (USFS). Roads analysis: informing decisions about managing the National Forest transportation system. Misc. Rep. FS-643. U.S. Department of Agriculture Forest Service, Washington, DC, USA, 1999. 222 p.
20. Lisle, T.E. Particle size variation between bed load and bed material in natural gravel bed channels. *Water Resour. Res.* **1995**, 31, 1107-1118.
21. Montgomery, D.R.; Buffington, J.M. Channel-reach morphology in mountain drainage basins. *Geol. Soc. Am. Bull.* **1997**, 109, 596-611.
22. Lawlor, S.M. Determination of channel-morphology characteristics, bankfull discharge, and various design-peak discharges in western Montana. Scientific Investigations Report 2004-5263. U.S. Geological Survey, Reston, VA, USA, 2004. 19 p.
23. Buffington, J.M.; Montgomery, D.R. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resour. Res.* **1997**, 33, 1993-2029.

24. Furniss, M.J.; Ledwith, T.S.; Love, M.A.; McFadin, B.C.; Flanagan, S.A. Response of road-stream crossings to large flood events in Washington, Oregon, and Northern California. USDA Forest Service. Technology and Development Program. 9877-1806-SDTDC, 1998. 14 p.
25. Cover, M.R.; May, C.L.; Dietrich, W.E.; Resh, V.H. Quantitative linkages among sediment supply, streambed fine sediment, and benthic macroinvertebrates in northern California streams. *J. N. Am. Benthol. Soc.* **2008**, 27, 135-149.
26. Wolman, M.G. A method of sampling coarse river-bed material. *Eos Trans. Am. Geophys. Union* **1954**, 35, 951-956.
27. Lisle, T.E.; Eads, R.E. Methods to measure sedimentation of spawning gravels. Research Note PSW-RN-411. Berkeley, CA, USA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, 1991. 7 p.
28. Choi, Y.T. *Principles of Applied Civil Engineering Design*. American Society of Civil Engineers Publications, Baltimore, MD, USA, 2004.
29. Wemple, B.C.; Swanson, F.J.; Jones, J.A. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surf. Proc. Land.* **2001**, 26, 191-204.
30. May, C.L.; Gresswell, R.E. Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. *Earth Surf. Proc. Land.* **2003**, 28, 409-424.
31. May, C.L.; Lee, D.C. The relationships among in-channel sediment storage, pool depth, and summer survival of juvenile salmonids in Oregon Coast Range streams. *N. Am. J. Fish. Manage.* **2004**, 24, 761-774.
32. Wellman, J.C.; Combs, D.L.; Cook, S.B. Long-term impacts of bridge and culvert construction or replacement on fish communities and sediment characteristics of streams. *J. Freshwater Ecol.* 2000, 15, 317–328.
33. May, C.L. Sediment and wood routing in steep headwater streams: an overview of geomorphic processes and their topographic signatures. *For. Sci.* **2007**, 53, 119-130.
34. Brock, W.; Fitzgerald, J.; Nunes, D.; Diestel, J. Tule Creek bridge pre-fabricated concrete bridge. On-line fish passage case study from the Shasta-Trinity National Forest. Redding, CA, USA, 2009. Available online: http://www.stream.fs.fed.us/fishxing/case/tule_creek/index.html. (accessed on 20 July 2013).
35. Keppeler, E.T.; Cafferata, P.H.; Baxter, W.T. State Forest Road 600: a riparian road decommissioning case study in Jackson Demonstration State Forest. California Forestry Note No. 120. California Department of Forestry and Fire Protection. Sacramento, California, USA, 2007. 22 p. Available online: http://www.fs.fed.us/psw/topics/water/caspar/pubs/Rd600DecomNote.pdf (accessed on 20 July 2013).
36. Maurin, L.P.; Stubblefield, A.P. Channel adjustment following culvert removal from forest roads in northern California, USA. *Ecol. Restor.* **2011**, 29, 382-391.
37. Harris, R.; Gerstein, J.; Cafferata, P. Changes in stream channel morphology caused by replacing road-stream crossings on timber harvesting plans in northwestern California. *West. J. Appl. For.* **2008**, 23, 69-77.

38. Brown, T.M. Short-term total suspended-solid concentrations resulting from stream crossing obliteration in the Clearwater National Forest, Idaho. M.S. thesis. University of Washington. Seattle, WA, USA, 2002.
39. Foltz, R.B.; Yanosek, K.A.; Brown, T.M. Sediment concentration and turbidity changes during culvert removals. *J. Environ. Mgmt.* **2008**, 87, 329-340.