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Streambed Sediment and Equivalent Roaded Area on the Klamath National Forest

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Beaver Creek before and after high-severity wildfire and intense rainfall
(Fine sediment <6.35mm = 47% and 60%).

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ABSTRACT

This report evaluates the cumulative effect of forest management activities on fine sediment deposition in 78 small streams in the Klamath National Forest. Conditions in managed streams are compared with reference conditions from 20 minimally disturbed watersheds in wilderness and roadless areas. Reference conditions were developed for four sediment indicators including percent fine sediment on the streambed surface, percent of the streambed subsurface less than 0.85mm and 6.4mm, and the portion of pools filled with fine sediment (V*). Of the 58 managed streams surveyed, 25 have fine sediment greater than the reference condition for at least one indicator. Significant correlations between equivalent roaded area and instream fine sediment establishes a link between the Forest Service road system and sediment deposition in streams that exceed water quality standards for sediment. The correlations are significantly improved by adding the area underlain by geologic parent materials that produce sand-sized particles as an explanatory variable. Thresholds for ERA are identified where regression models predict that instream fine sediment will exceed the reference condition at the 95^{th} confidence limit. Watersheds with sandy geology are more sensitive to land disturbance and have a lower threshold for ERA than non-sandy watersheds. Wildfire and subsequent debris flows from areas of high soil burn severity caused a short-term increase in fine sediment that far exceeds the sedimentation from other sources. Long-term chronic sediment sources from high road densities continue cause exceedances after the short-term pulse of sediment from the fires routed through the stream network. Watersheds with low road densities and ERA are resilient to the effect of fires and had only a short-term increase above the reference condition. Our data shows that ERA is a valid indicator of the cumulative effects of land management on in-stream sediment, and establishes thresholds for ERA that are correlated with exceedance of water quality standards for fine sediment.

Contents

INTRODUCTION

This report is an assessment of in-stream sediment monitored on the Klamath National Forest (KNF) between 2009 and 2020. The KNF sediment monitoring program is required by the North Coast Regional Water Quality Control Board as a condition for permitting management activities on federal land (NCRWQB 2015). Nearly all streams on the KNF are listed under Clean Water Act section 303(d) for violation of water quality standards for in-stream sediment or stream temperature. Total Maximum Daily Loads (TMDL) for the Klamath, Scott, Shasta, and Salmon Rivers require the Forest Service to control human-caused sediment discharges in order to meet the sediment load reductions identified in the TMDLs. Most of the sediment discharge sites on the KNF are associated with logging roads, erosion from road surfaces and landslides triggered by stream crossing failures during floods. Many roads have been upgraded to improve drainage and prevent road failures, but thousands of potential sediment sites remain untreated. Sediment monitoring is required to show whether the TMDL restoration actions and Forest Service policies such as road Best Management Practices (BMPs) are effective at attaining State water quality standards at a watershed scale.

In-stream sediment monitoring is also required by the KNF Land and Resource Management Plan to validate the Forest Service Equivalent Roaded Area (ERA) model. The ERA model is used in project planning to assess the cumulative effects of disturbances such as roads, timber harvest, and fire. In-stream sediment monitoring is needed to validate that increasing ERA is correlated with deposition of fine sediment in stream channels, and that ERA thresholds for watershed disturbance represent a high risk of exceeding water quality standards.

The objectives of the monitoring program are to answer the following questions.

1. What is the reference condition for streambed fine sediment on the Klamath National Forest?
2. Are Forest Service water quality policies effective at maintaining or restoring desired conditions for fine sediment that support beneficial uses?
3. Identify thresholds for the Forest Service cumulative watershed effects models that predict attainment of desired conditions for streambed fine sediment.

METHODS

Compliance Criteria

The North Coast Water Board has developed desired conditions for in-stream sediment indictors that are expected to support beneficial uses and meet water quality standards for sediment (Table 1, NCRWQCB 2006). However, the state’s desired condition values were derived from watersheds underlain by a different geology and may not reflect the size and volume of sediment produced from the parent geologic material on the Klamath National Forest. To help identify more appropriate values for the desired condition, the Klamath National Forest and the North Coast Regional Water board agreed to monitor sediment in reference streams to develop local values for the indices in Table 1. A detailed description of the sediment sampling protocols and field forms are available in the Klamath National Forest stream monitoring field guide (USFS, 2011).

Table 1. Parameters used to measure in-stream fine sediment

Parameter	Survey Method
Fraction of Pool Volume filled with Sediment (V*)	Hilton and Lisle (1993) USFS (2011)
Subsurface Sediment < 0.85mm (%)	Schuet-Hames (1999) USFS (2011)
Subsurface Sediment < 6.4mm (%)	Schuet-Hames (1999) USFS (2011)
Surface Sediment < 2.0mm (%)	Cover (2008) USFS (2011)

Selection of Watersheds and Sample Sites

A network of monitoring watersheds was developed that covers most of the major tributary streams on the Klamath National Forest. One sample site was selected in each watershed at a "response reach". Response reaches usually have the lowest stream gradient in the watershed and are the locations most likely to accumulate fine sediment in response to increased sediment supply. Response reaches are typically located near the mouth of the stream and reflect the cumulative effect of sediment input from all sources in the watershed. Only gravel-bed channels were surveyed. Meadow streams with silt or clay beds were avoided due to inapplicability of the sampling methods in those stream types. The minimum length of response reaches was set at 500 meters with a channel gradient less than 6 percent. The resulting pool of sample sites contains 78 watersheds that drain about 75% of total area on the Forest (Figure 1). Most of the remaining 25% of the drainage area cannot be monitored with stream surveys because it is located in areas that do not have surface streams, has access limitations due to private land, or drains to very steep or intermittent stream channels.

Managed and Reference Watersheds

Each watershed on the Forest is designated as either a managed or a reference watershed. Reference streams are located in watersheds that have minimal human influence and represent the natural range of conditions resulting from environmental variation. Reference watersheds are used to define desired conditions and serve as benchmarks to measure effects in managed watersheds. Reference watersheds were selected using the guidance from Stoddard (2009), Ode (2009), and the criteria in Table 2. Candidate reference streams that meet the criteria were validated using field observations and best professional judgment. Most of the reference watersheds are located in wilderness and roadless areas that are managed for natural conditions and ecological process within a mostly pristine landscape. All of the reference watersheds have a history of disturbance by wildfire and floods that are important components of the natural variability. Managed watersheds include all watersheds that do not meet the criteria for reference streams. The physical characteristics of the reference watersheds have a similar range as the managed streams and are representative of the natural background condition of the managed watersheds (Table 3).

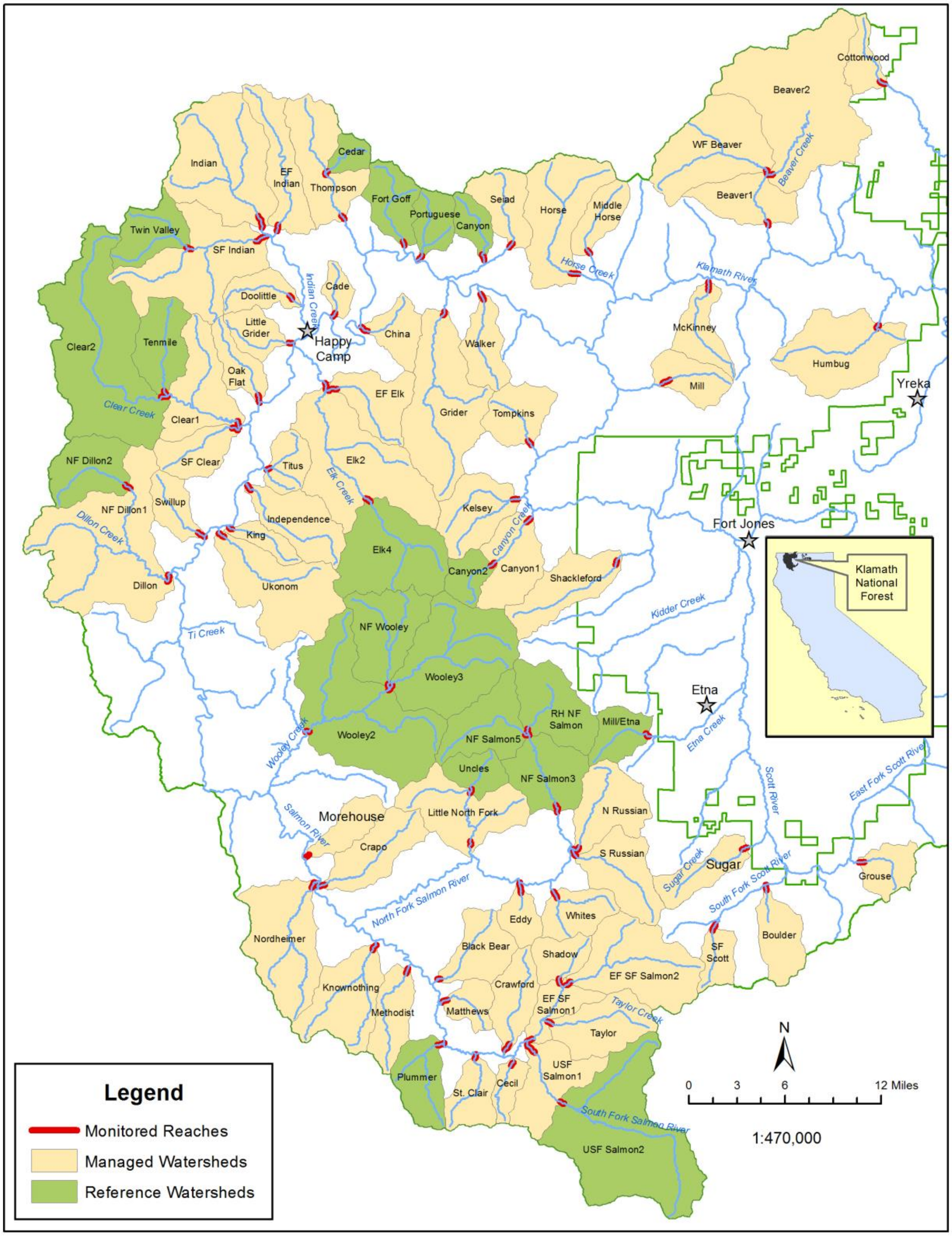


Figure 1. Watersheds and monitored reaches.

Table 2. Reference watershed criteria.

Disturbance	Criteria
Road density	Less than 0.19 km/km^2 (0.30 mi/mi^2) with no significant road failures.
Grazing	No BMP violations. Most have no grazing.
Mining	No significant sediment input or point sources (metals or pH). Most have only prospects.
Timber harvest	Equivalent roaded area from timber harvest and roads is less than 0.4 percent of the watershed area.
Wildfire and other natural disturbances	Wildfire is included unless there has been substantial disturbance by suppression activities such as dozer lines in riparian areas.

Table 3. Characteristics of reference and managed watersheds

Watershed Characteristics	Reference Streams (n = 20)			Managed Streams (n = 58)		
	Average	Maximum	Minimum	Average	Maximum	Minimum
Drainage Area (km^2)	71	299	13	65	272	12
Mean Elevation (m)	1434	1738	1147	1282	1840	760
Precipitation (Mean Annual) (in)	73	100	53	57	87	35
Road Density (km/km^2)	0.03	0.19	0.00	1.61	3.58	0.14
Equivalent Roaded Area (%)	1.0	4.7	0.0	3.4	9.9	0.2
Sandy geology (% of drainage area)	44	95	13	48	100	0
Channel Gradient (%)	3.4	6.0	1.0	2.9	5.6	0.3

Stratification by Geology

Instream fine sediment is known to be more sensitive to land management in watersheds underlain by granitic geologic parent material that weathers to produce large amounts of sand. To quantify their sensitivity to disturbance all bedrock map units plus geomorphic landforms were designated as either sandy or non-sandy based on the ability of the dominant parent material to produce sand-sized sediment (Table 4). This stratification is based on criteria from Lisle and Hilton (1999) who found that the amount of sediment in pools (V*) varies with the size of the sediment particles eroded from different parent materials. The chief determining criteria is the relative abundance of silica (SiO2) in the bedrock. Silica-rich rocks typically erode to produce sand-sized particles, while silica-poor rocks generate silt and clay-sized sediments. Each watershed on the Forest was designated as either a sandy or non-sandy watershed if greater than or less than 50% of the drainage area is underlain by sand-producing geology.

Table 4. Bedrock units used to stratify watersheds into sandy and non-sandy geologies.

Bedrock units producing abundant sand	Bedrock units producing modest or little sand
Granitic rocks, quartz-bearing schistose rocks, shale, siltstone, sandstone (greywacke), conglomerate, chert, quartzite, diorite, unconsolidated materials (e.g., glacial deposits, stream terraces, outwash deposits), tuff, pyroclastic rocks, cinders, rhyolite, rhyodacite, pumice	Slate, gabbro, undifferentiated metamorphic, undifferentiated metasediments, mudstone, ultramafic rocks, limestone, mélange units, undifferentiated volcanic rocks (including basalt, andesite, dacite), undifferentiated metavolcanic rocks

Equivalent Roaded Area

Disturbance from all past and current management activities and wildfire is modeled for each watershed using the Forest Service Equivalent Roaded Area (ERA) model (USFS, 1990). ERA is an index of cumulative watershed disturbance that is used to relate watershed management with impacts to in-stream beneficial uses. ERA is calculated using coefficients to weight management activities relative to the effects of a road in terms of altering sediment budgets and runoff per unit area of disturbance. Coefficients have been developed for a wide range of management activities depending on the degree of soil disturbance and percent of vegetation removed. Recovery of a disturbed site is modeled by reducing the coefficients over time until ERA returns to the natural undisturbed state. The cumulative sum of all the weighted disturbances in a watershed gives the total equivalent roaded area, which is expressed as a percentage of the watershed drainage area. The methods and assumptions used to calculate ERA are described in USFS (2020).

The ERA procedure estimates a threshold of concern (TOC) as an upper limit to ERA where the cumulative effect of land use has a high risk of adversely effecting in-stream beneficial uses. The TOC is estimated by relating in-stream conditions to ERA and then setting the TOC to avoid significant adverse impacts. The ERA model assumes that watersheds containing a high percentage of sensitive land units, such as highly erodible soils, unstable slopes, or the presence of low-gradient stream channels, have a lower TOC than watersheds with fewer sensitive lands. A goal of the KNF sediment monitoring program is to identify a TOC that attains TMDL targets for fine sediment and avoids adverse impacts to beneficial uses.

RESULTS

Between 2009 and 2020 the KNF measured a total of 209 sediment samples. Each managed stream was measured at least twice. Reference streams were re-sampled three times with each sample taken 2 to 4 years apart. Two reference sites in Wooley Creek have just two samples each due a trail washout that prevents access. A few managed streams were sampled up to 5 times in order to measure the effects of high severity wildfire. Most of the data were collected by the Northern California Resource Center, a non-profit organization working in a partnership with the Forest Service. Quality control of the field work and data is considered good with very few problems encountered during field sampling. There were no floods larger than about a 5-year event during the sampling period, but a large runoff event and debris flows occurred from burned areas in the summer of 2015. Mean July stream flows in 2011 were the 3rd highest on record due to a heavy snowpack which kept stream flows high late into the summer.

Table 6. Peak stream flows at Indian Creek near Happy Camp, CA, 2009 to 2019.

Year	Discharge (cfs)
2009	3,940
2010	4,090
2011	2,600
2012	6,140
2013	7,400
2014	3,570
2015	9,770
2016	7,360
2017	11,300
2018	2,630
2019	6,570
2020	3430

Reference Conditions and Natural Variability

Fine sediment in reference streams on the KNF has a normal bell-shaped distribution (Figure 2). The distribution is skewed to the right with a tail of high values in watersheds affected by high-severity wildfire. The highest reference values were in Elk, Uncles, and Ft. Goff Creeks which had large portions of their watersheds affected by high severity fire (Figure 3).

An upper boundary for desired conditions is identified at the trough that separates the bell-shaped portion of the distribution from the high values affected by recent high severity wildfire. The 90th percentile is a good estimate of desired conditions because it plots at approximately the break point in the curve. The 90th percentile includes most of the natural range of variability in the bell-shaped portion of the distribution but excludes adverse effects from severely burned watersheds at the upper end. The reference condition is not considered as a single value but rather as a distribution with an upper bound at the 90th percentile.

Management Effects on Streambed Sediment

Conditions in managed streams are evaluated by comparing fine sediment in each managed stream to the 90th percentile of the reference values. Of the 58 managed streams surveyed, 33 have fine sediment less than the reference condition for all four indicators (Table 3). These streams are attaining desired conditions for fine sediment. Some streams initially had fine sediment greater than the reference in the first sample but dropped below the reference condition in the 2nd or 3rd sample. Fine sediment was greater than the reference condition for at least one indicator in 25 managed streams (Table 3). These streams are not attaining desired conditions for in-stream fine sediment. A comparison of the entire population of managed streams to reference streams shows the medians for all four sediment indicators are higher in managed streams (Figure 3).

The source of sediment in watersheds exceeding reference conditions is estimated using Equivalent Roaded Area (ERA). Wildfire is the largest disturbance in Crapo, Independence, Grider, South Russian, and Whites Gulch (Figure 4). These streams have relatively little roaded area or timber harvest and mostly likely exceed the reference condition due to erosion from high severity wildfire. All other streams that exceed the reference condition have high ERA from roads and timber harvest, suggesting that sedimentation is due to the cumulative effects of those management activities.

Table 7. Summary statistics for natural sediment conditions in reference streams.

	Pool Sediment (V*)	Surface Sediment <2mm (%)	Sub-Surface Sediment <6.35mm (%)	Sub-Surface Sediment <0.85mm (%)
N	60	60	58	58
Mean	0.05	2.8	37.3	10.9
Maximum	0.13	12.1	61.6	20.8
90th percentile	0.11	6.5	47.7	17.7
85th percentile	0.09	4.2	46.0	15.9
75th percentile	0.07	3.6	43.6	13.4
Median	0.04	2.2	36.8	10.2
Minimum	0.01	0.3	19.4	2.7
Standard Deviation	0.03	2.3	8.6	4.4

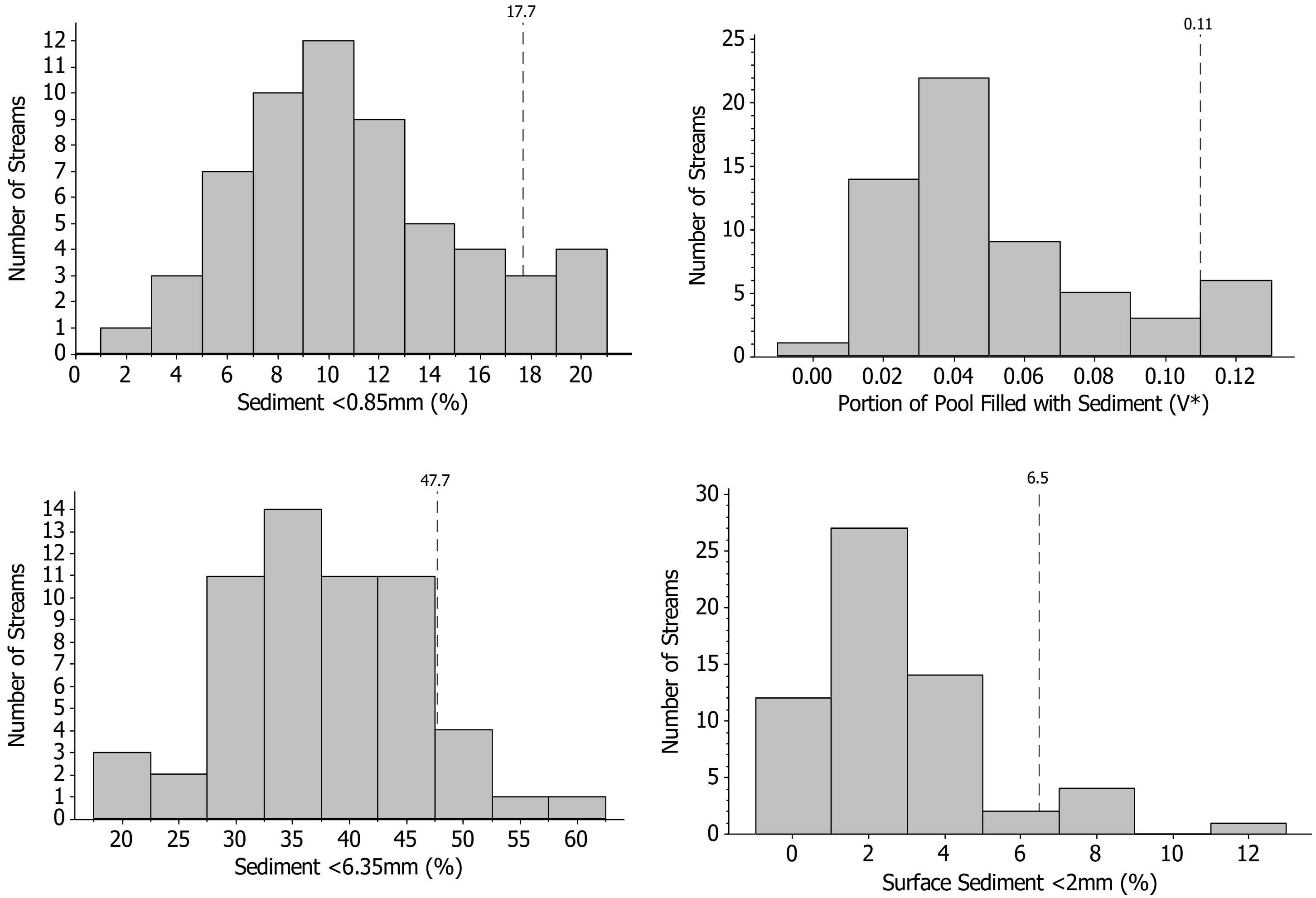


Figure 2. Distribution of fine sediment in reference streams. The 90th percentile is shown by dashed lines. Desired conditions include the portion of the distribution below the 90th percentile (left of the dashed lines). Most of the high sediment values above the 90th percentile are due to high severity wildfire and are excluded from the desired condition.

Table 8. Sediment in reference streams. Streams in bold exceed the 90th percentile.

Stream	Sandy Geology (%)	Road Density (mi/m^2)	Years Sampled	Pool Sediment (V*)				Surface Sediment <2mm (%)				Subsurface <6.38mm (%)				Subsurface <0.85mm (%)			
				1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Canyon Seiad	95	0.04	2010, 2013, 2017	0.092	0.069	0.048		3.5	4.1	2.5		38.7	32.7	32.9		12.1	7.4	8.0	
Canyon/Scott 2	39	0.21	2009, 2012, 2017 2018	**0.112**	**0.122**	0.073	0.062	3.2	**7.2**	1.9	2.3	42.8	39.3	47.7	36.2	10.9	11.1	14.6	9.1
Cedar	23	0	2009, 2012, 2018	0.09	0.051	0.05		2.4	3.2	1.0		40	38.3	47.7		15.2	9.6	14.9	
Clear 2	19	0	2010, 2013, 2018	0.029	0.027	0.026		3.3	1.6	0.3				31.7				4.6	
Elk 4	76	0	2009, 2012, 2018	**0.121**	0.043	0.031		4.2	3.8	2.3		**61.6**	**56.2**	46.7		**20.8**	17.7	14.4	
Fort Goff	82	0.01	2009, 2012, 2017	0.094	0.074	0.032		2.2	3.8	3.6		**51.1**	45.4	43.9		**19.6**	17.7	**19.8**	
Mill/Etna	30	0.1	2009, 2012,2017, 2018	0.032	0.034	0.007	0.017	2.1	1.5	0.5	0.7	32.8	31.4	19.4	30.7	10.3	8.5	2.7	5.7
N.F. Dillon 2	26	0.24	2010, 2013, 2018	0.030	0.028	0.024		2	1.4	1.3		28.7	38.5	35.2		6.8	9.5	9.6	
NF Salmon 3	15	0.07	2010, 2013, 2018	0.044	0.030	0.025		0.4	2.2	0.5		32.9	34.7	23.4		10.1	5.4	6.6	
NF Salmon 5	32	0	2010, 2013, 2018	0.077	0.065	0.046		12.1	0.8	1.3		29.4	33.3	20.1		8.3	6.5	4.6	
NF Wooley	46	0	2010, 2014	0.069	0.040			**7.5**	3.7			29.8	35.8			8.0	9.3		
Plummer	13	0	2010, 2013, 2018	0.035	0.033	0.024		0.6	2.2	0.7		29.5	38.0	30.3		8.6	9.4	6.5	
Portuguese	88	0.1	2009, 2012, 2017	0.074	0.045	0.036		2.5	3.4	1.5		45.6	40.4	35.9		12.7	12.8	11.9	
Right Hand NF Salmon	13	0	2010, 2013, 2018	0.051	0.034	0.022		1.6	1.1	0.8		32.9	40.0	43.3		12.4	12.5	17.2	
Tenmile	50	0	2010, 2013, 2018	0.026	0.016	0.016		3.6	2.2	0.4		38.4	43.5	31.6		10.3	13.0	8.5	
Twin Valley	22	0	2009, 2012, 2017	0.054	0.025	0.015		1.2	2.1	0.6		30.1	21.9	24.1		7.8	3.5	5.2	
Uncles	54	0	2009, 2012, 2017	**0.111**	**0.127**	0.082		**7.2**	**8.8**	3.3		47.0	**51.0**	43.8		**19.9**	15.8	16.0	
Up. S.F. Salmon 2	95	0.31	2009, 2012, 2017	0.05	0.037	0.042		5.0	2.8	2.5		41.6	45.9	45.3		15.9	13	10.2	
Wooley 2	40	0.03	2010, 2012, 2017	0.03	0.032	0.03		2.9	1.4	0.9		34.2	37.3	37.7		10.8	12.2	8.7	
Wooley 3	21	0	2010, 2014	**0.127**	0.048			**6.7**	4.7			33.6	29.4			11.5	7.8		

Table 9. Sediment in managed streams. Streams in bold exceed the reference condition for at least one indicator. *Sample sites at Grider and Walker Creeks were directly buried by debris flow landslides in 2015.

Stream	Sandy Geology (%)	Road Density (mi/m^2)	Years Sampled	V*					Surface Sediment <2mm (%)					Subsurface <6.38mm (%)					Subsurface <0.85mm (%)				
				1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th
Beaver 1	66	5.12	2010, 2013 2015 2016, 2017	0.053	0.056	**0.812**	0.034	0.030	3	2.4	**13.3**	3.0	3.6	44.2	47.4	**59.9**	**57.0**	**50.2**	**18.2**	**18.2**	**26.4**	**28.0**	**19.1**
Beaver 2	65	5.14	2010, 2013	0.076	0.074				3.6	6.3				44.0	44.4				16.0	**19.3**			
Black Bear Ck	26	2.62	2012, 2015	0.053	0.066				1.5	5.3				47.3	41.6				**20.0**	13.8			
Boulder	90	2.38	2011, 2015	0.073	0.075				4.2	**7.5**				41.6	47.7				12.9	12.7			
Cade	72	4.47	2009, 2013 2019	**0.190**	**0.236**	**0.120**			**8.0**	**7.8**	4.2			**52.0**	**49.7**	**49.7**			**22.5**	**20.6**	**20.5**		
Canyon Scott 1	32	1.07	2010, 2013, 2019	0.053	0.042	0.030			1.8	0.9	0.8			28.6	33.0	39.5			9.5	7.4	10.5		
Cecil Creek	73	3.8	2012, 2015	0.074	0.075				2.4	2.3				35.1	39.0				9.0	13.7			
China	1	5.57	2011, 2015	0.088	0.097				**8.6**	6.5				47.4	**50.1**				**23.2**	15.6			
Clear 1	26	0.23	2009, 2013, 2019	0.013	0.02	0.030			1.5	0.6	0.8			28.5	27.4	16.4			9.0	4.7	3.8		
Cottonwood	97	0	2011, 2014	**0.493**	**0.356**				**14.6**	**19.3**				**57.5**	**61.3**				15.6	**22.7**			
Crapo	68	0.9	2011, 2014	0.094	0.099				4.3	2.9				**54.1**	**63.1**				**18.4**	**18.6**			
Crawford	73	3.08	2011, 2014	0.095	0.082				**7.0**	4.4				43.4	**53.2**				**19.0**	**22.1**			
Dillon	30	0.76	2009, 2013, 2019	0.065	0.071	0.070			0.3	1.3	0.5			28.0	38.1	40.8			7.5	9.8	7.4		
Doolittle Indian	35	4.61	2012, 2015	0.055	0.059				2.6	4.9				32.5	39.6				8.0	8.5			
East Fork Elk	3	3.19	2011, 2015 2016	0.065	0.040	0.075			**9.0**	**7.7**	**9.9**			45.6	40.6	31.7			15.2	13.2	10.3		
East Fork Indian	72	2.54	2011, 2014	0.099	0.087				**9.3**	3.2				40.7	46.0				17.4	15.1			
Eddy	43	4.42	2011, 2014	0.076	0.045				3.4	6.4				47.1	47.6				14.3	12.3			
EF SF Salmon 1	74	1.95	2011, 2015	0.029	0.033				1.2	2.1				35.2	26.0				11.6	7.3			
EF SF Salmon 2	71	1.59	2011, 2015	0.028	0.034				1.4	2.9				35.0	45.2				8.8	12.1			
Elk 2	51	1.71	2011, 2015 2016 2017	0.049	0.038	0.035	0.093		**6.7**	4.5	3.4	6		36.6	45.2	**51.9**	**54.8**		**18.9**	14.4	**20.6**	**19.1**	

Grider	31	1.42	2009, 2013, 2015 2016, 2017	0.054	0.044	**1.000***	0.066	0.033	3.7	2.5	**16.1***	**9.2**	3.5	47.0	32.2	**69.0***	46.6	45.8	15.8	9.2	**42.1***	17.0	15.2
Grouse Scott	44	3.75	2011, 2015	0.069	0.076				0.3	2.3				42.5	42.1				17.1	8.2			
Horse	96	4.54	2010, 2013 2017	**0.237**	**0.220**	0.098			4.3	**11.0**	4.4			46.6	45.2	**57.1**			**20.0**	16.4	**22.4**		
Humbug	31	2.63	2010, 2013 2019	**0.136**	**0.126**	0.050			**6.8**	4.5	2.3			44.0	44.3	37.4			16.0	14.3	13.5		
Independence	40	1.54	2011, 2015	0.08	0.109				6.4	6.1				40.6	37.6				16.3	14.8			
Indian 3	9	3.62	2011, 2014	0.072	0.057				6.1	**8.2**				43.7	47.1				17.7	13.2			
Kelsey	38	1.15	2011, 2014 2015 2018	0.061	0.045	0.053	0.086		4.1	3.8	0.2	6.3		44.2	41.5	43.6	**55.7**		12.9	11.3	12.1	**27.0**	
King Creek	8	1.28	2012, 2015	0.064	0.036				5.2	3.1				40.8	40.1				10.6	15.3			
Knownothing	27	2.29	2011, 2014	0.100	0.067				2.3	2.4				23.2	45.9				8.0	13.7			
Little Grider	1	2.75	2009, 2013	**0.139**	0.062				5.0	3.2				46.0	**53.2**				16.1	14.7			
Little N.F. Salmon	57	0.61	2009, 2013 2019	0.099	0.081	0.080			3.7	**7.4**	2.2			43.4	**50.7**	37.6			13.9	13.2	10.5		
Matthews	33	2.66	2011, 2015	**0.138**	0.109				3.9	2.3				40.6	46.6				14.5	16.1			
McKinney	35	4.29	2010, 2014, 2020	**0.239**	**0.286**	**0.169**			**13.1**	**7.4**				45.5	44.0	**59.1**			**21.8**	**23.9**	**29.5**		
Methodist	5	2.6	2011, 2014	0.070	0.071				1.8	3				45.1	**54.4**				11.6	10.1			
Middle Horse	100	5.77	2009, 2013 2019	**0.246**	**0.289**	**0.160**			**7.9**	**27.1**	**8.2**			**52.2**	**49.0**	**52.5**			**24.5**	**18.8**	**22.0**		
Mill Ck Scott	10	4.49	2011, 2014	0.068	0.074				3.1	**8.3**				**58.6**	**57.8**				**23.4**	**25.5**			
Nordheimer	21	0.32	2011, 2014	0.043	0.038				4.0	0.9				36.0	29.9				10.3	8.7			
North Russian	34	1.89	2011, 2015 2016	0.076	0.082	0.084			0.7	4.0	3.8			35.1	38.7	36.6			8.6	12.3	13.7		
Oak Flat	1	1.55	2011, 2014	0.062	0.051				**10.0**	4.7				44.8	**55.4**				15.5	**19.4**			
S.F. Clear	12	2.34	2011, 2015	0.022	0.022				**7.1**	1.5				45.7	44.7				14.1	12.8			
S.F. Indian	17	1.67	2011, 2014	0.034	0.025				5.3	2.5				43.6	38.9				11.1	9.4			
Seiad Creek 2	94	1.83	2012, 2015	0.026	0.041				3.3	1.8				45.7	40.9				17.4	13.6			
SF Scott River 4	65	3.13	2011, 2014	0.070	0.087				3.2	1.5				**54.2**	**54.0**				17.7	**20.8**			
Shackleford	37	1.83	2009, 2013 2019	0.037	0.029	0.040			2	4.9	0.9			47.6	35.5	39.7			17.1	12.9	10.2		

Shadow	95	2.75	2012, 2015 2020	0.069	0.091	0.086			**7.7**	**7.9**				**55.6**	**57.8**	40.8			**23.4**	**25.5**	**19.9**		
South Russian	89	1.38	2011, 2015 2016 2017	0.056	**0.230**	0.100	0.095		4.5	**9.9**	**7.8**	4.8		46.9	**65.1**	**64.9**	**50.8**		13.2	**21.9**	**19.0**	14.7	
St Clair Creek	39	1.12	2012, 2015	0.054	0.044				2.6	0.9				42.6	44.0				9.8	10.8			
Sugar Creek	98	1.72	2012, 2015	0.080	0.091				4.9	4.3				**56.5**	47.4				14.7	12.8			
Swillup	29	1.75	2010, 2013 2019	**0.120**	**0.112**	0.030			**7.5**	3.4	2.1			39.7	46.9	39.5			12.3	12.6	11.4		
Taylor	74	2.23	2011, 2014	0.092	**0.111**				4.7	**10.2**				46.4	43.1				**18.0**	15.5			
Thompson 2	31	0.9	2009, 2013, 2019	0.031	0.033	0.020			1.9	1.7	1.1			42.0	36.5	24.3			12.6	8.8	7.6		
Titus Creek	0	2.95	2012, 2015	**0.112**	0.074				**11.4**	3.4				43.5	42.2				11.4	11.1			
Tompkins	61	2.86	2011, 2014 2015	0.081	0.083	0.082			2.2	2.8	2.9			**63.3**	49.2	40.6			**27.8**	**20.5**	13.1		
Ukonom	77	0.96	2011, 2014	0.060	0.043				4.8	2.2				**51.3**	38.6				17.3	10.4			
Upper SF Salmon	95	0.79	2011, 2014	0.074	**0.116**				2.8	1.9				35.0	39.4				6.6	7.6			
W.F. Beaver	77	5.5	2009, 2013 2019	**0.143**	**0.124**	0.060			3.1	6.1	2.2			45.6	45.5	**48.4**			16.9	**20.3**	17.3		
Walker	71	3.82	2011, 2014 2015 2016, 2017	0.103	**0.111**	**0.892***	0.023	0.035	3.8	**8.4**	**54.2***	5.3	3.3	**50.8**	**52.3**	**88.1***	**54.4**	**72.2**	17.0	14.5	**36.7***	**20.5**	**32.1**
Whites	66	2.22	2011, 2014, 2015 2016, 2017	0.044	0.05	0.034	0.049	0.058	2.6	1.4	2.8	5.5	3.2	34.4	35.0	46.8	**47.9**	**40.3**	10.6	9.3	19.4	15.9	11.3

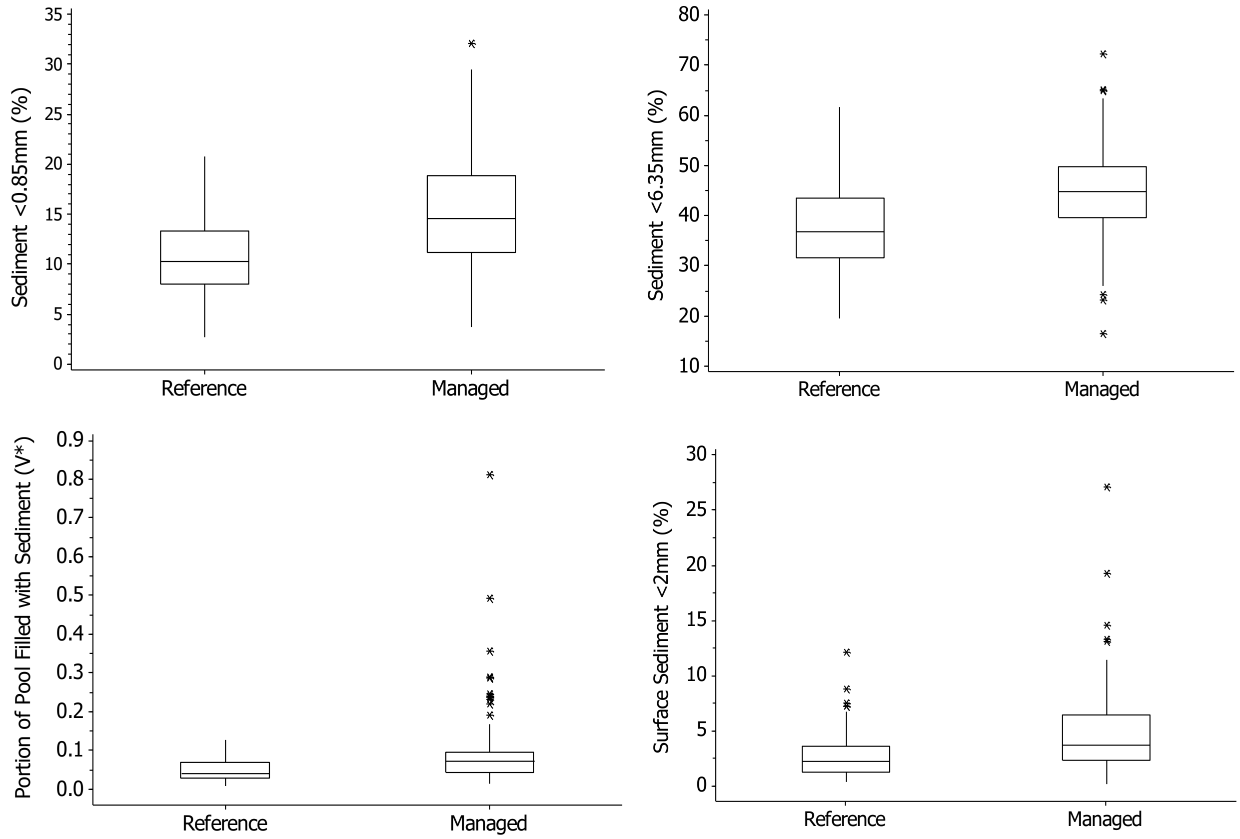


Figure 3. Fine sediment in reference and managed streams for four sediment indicators. Boxes show medians and quartiles, whiskers are 1.5 times the quartile range. Managed streams have significantly higher fine sediment than reference streams (Mann-Whitney at p <0.05).

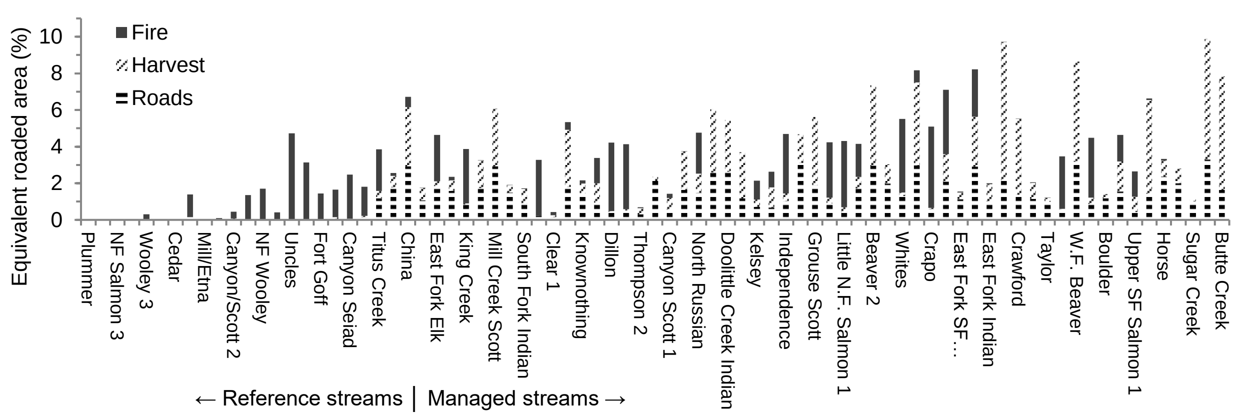


Figure 4. Percent of equivalent roaded area from wildfire, roads, and timber harvest. Data from 2nd and 3rd samples.

Streambed Sediment Response to Equivalent Roaded Area and Road Density

The relationship between equivalent roaded area and deposition of fine sediment in streambeds was evaluated using ordinary least squares regression. Significant positive correlations were found between percent equivalent roaded area and all four sediment indicators (Table 10, Figure 5). Road density was also significantly correlated with all four sediment indicators. The correlations are weak, explaining only 12 to 40 percent of the variability. Percent sandy geology was significantly correlated with all sediment indicators and it improved the r^2 of the correlations. Although percent sandy geology had only a small effect it is included in the regression equations due to its known influence on fine sediment in local streams. Other environmental factors including elevation, drainage area, precipitation, percent of the drainage in the rain-on-snow zone did not significantly improve the correlations between ERA and percent fine sediment when added as explanatory variables.

Thresholds for Equivalent Roaded Area and Road Density

Thresholds for ERA are identified where regression models predict attainment of the reference condition for streambed sediment <0.85mm. To account for the large scatter in the data a threshold is identified where the lower 95% confidence limit crosses the reference condition (Figure 5). The thresholds vary with geology and generally increase as the percentage of the watershed underlain with sandy geology increases (Figure 6). Watersheds with a higher percentage of sandy geology have a high natural sensitivity and can tolerate less land disturbance than watersheds with a low percentage of sandy geology. Thresholds for ERA are listed in Appendix A and range between 5.7 and 9.1 depending on geology.

Table 10. Relationships between streambed sediment, sandy geology, equivalent roaded area, and road density. Equation (1) should be used for effects analysis because it has the best r^2 and strongest link to beneficial uses.

	Sediment Indicator	Model	N	R^2	*P*	S
(1)	Subsurface Sediment <0.85mm (%)	8.52 + 1.26(ERA)+ 0.0322(%Sandy)	206	0.40	0.000	4.2
(2)		8.52 + 1.65(Rd Density) + 0.0486(%Sandy)	205	0.38	0.000	4.3
(3)	Subsurface Sediment <6.35mm (%)	33.8 + 1.68(ERA) +0.0740(%Sandy)	206	0.30	0.000	7.8
(4)		33.8 + 2.08(Rd Density) + 0.102(%Sandy)	206	0.28	0.000	8.0
(5)	V* Portion of Pool with Sediment	0.0234 + 0.0103(ERA) + 0.000469(%Sandy)	209	0.17	0.000	0.072
(6)		0.0226 + 0.0135(Rd Density) + 0.000632(%Sandy)	209	0.16	0.000	0.072
(7)	Surface Sediment <2mm (%)	2.36 + 0.578(ERA)	207	0.16	0.000	3.1
(8)		2.83 + 0.711(Rd Density)	207	0.12	0.000	3.2
	Where:					
	ERA	Equivalent roaded area (% of watershed area)				
	% Sandy	Percent of watershed with sandy geology				
	Rd Density	Road length per watershed area (mi/mi^2)				

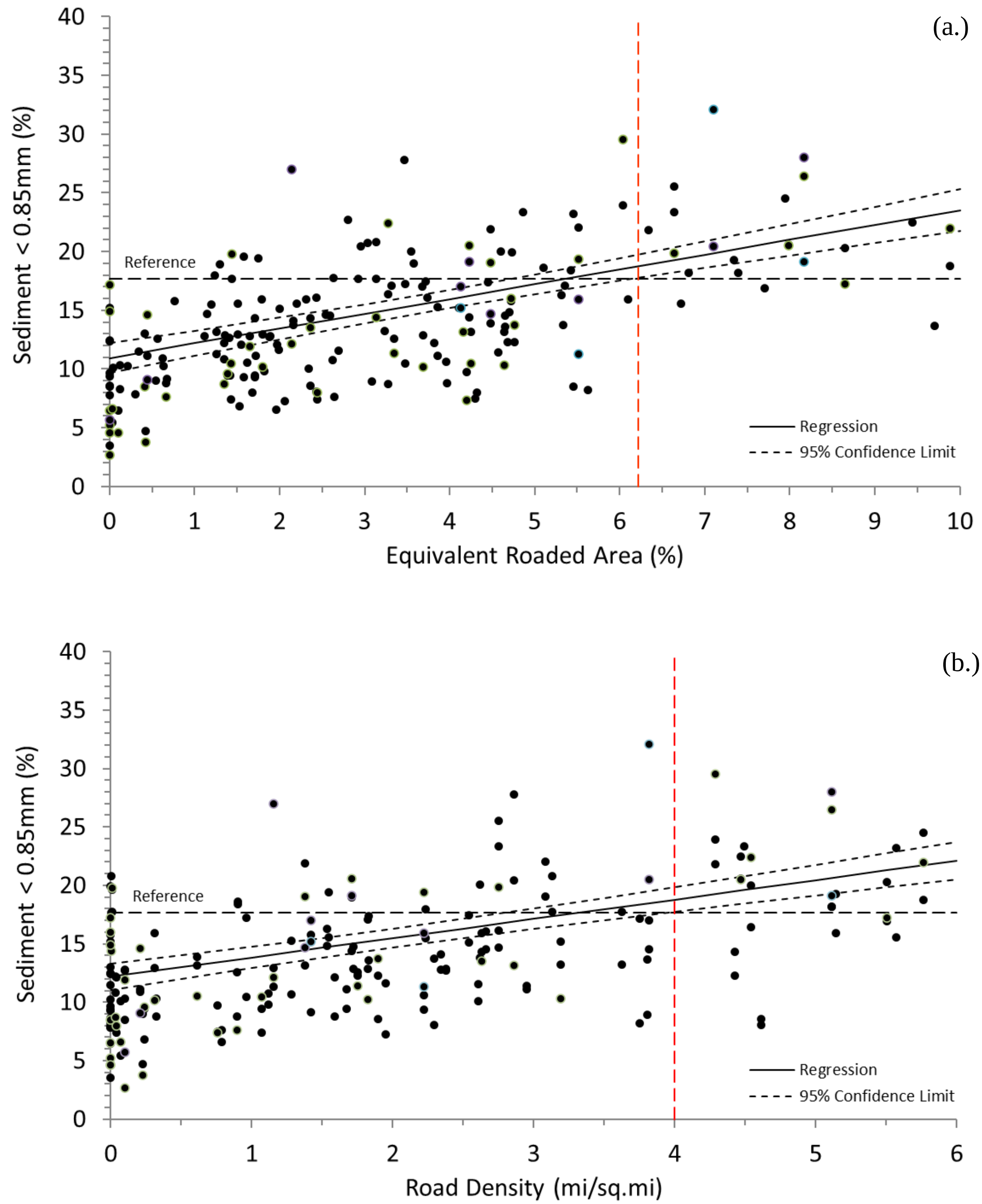
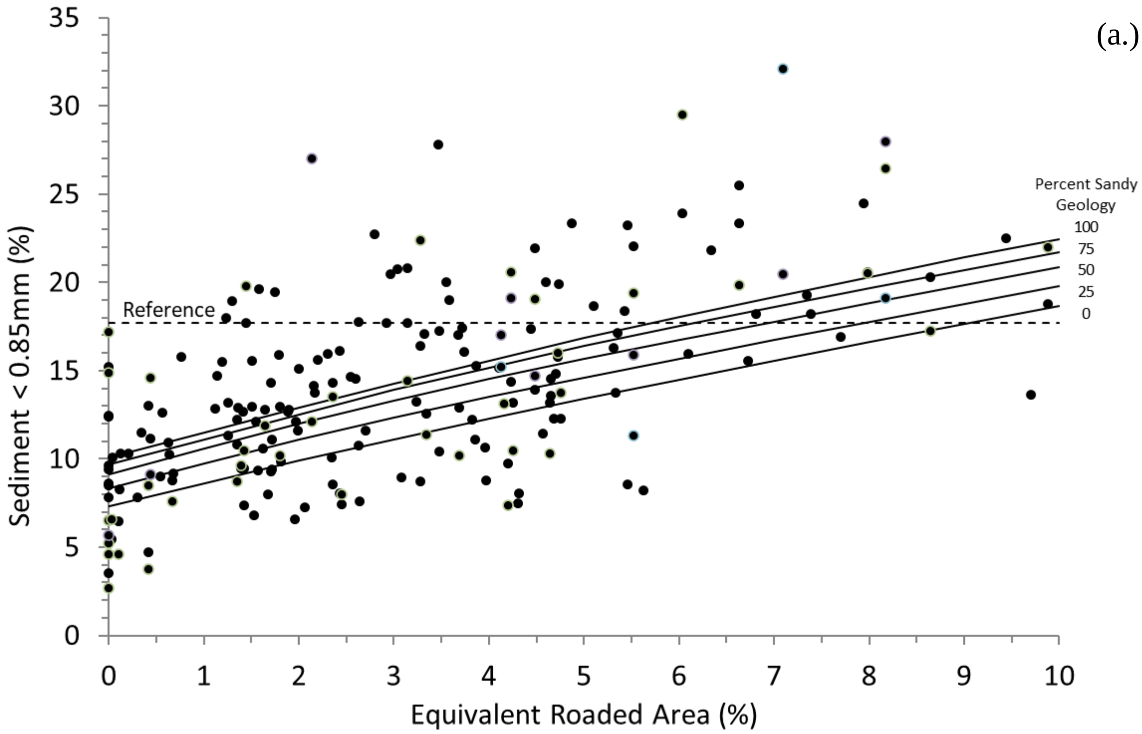


Figure 3. Response of streambed sediment to equivalent roaded area and road density. Regressions are from Table 10 models 1 & 2 with 75% sandy geology. Thresholds are identified where the lower confidence limit intersects the reference condition, shown by the vertical line. Grider and Walker Creek samples that were impacted by debris flows are not included in the regressions.



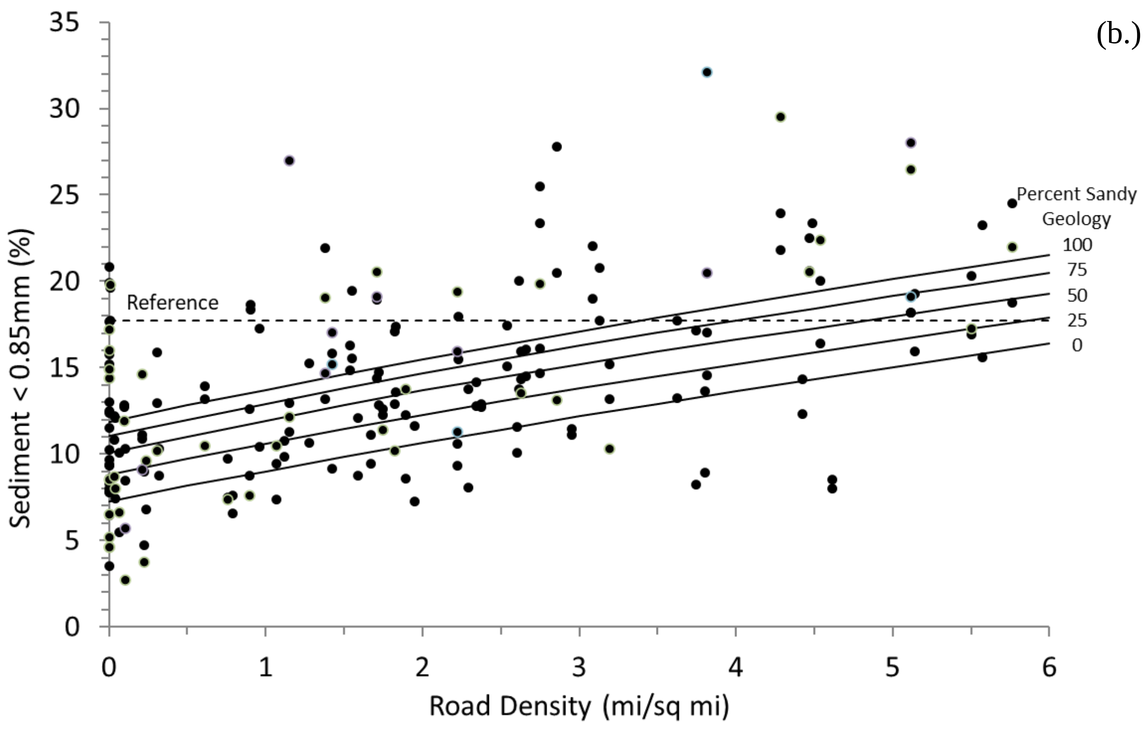


Figure 4. Lower 95% confidence limits for correlations between streambed sediment <0.85mm and equivalent roaded area and road density. Thresholds are identified where the confidence limits cross the reference condition of 17.7% fine sediment. For example: the threshold of concern for ERA in watersheds with 75% sandy geology is 6.2%.

Effect of Fires on Streambed Sediment

The effect of wildfire on in-stream sediment was evaluated in five watersheds that burned at a high-severity in 2014 (Table 5). Most of the sites had two measurements before and three measurements after the fires which allows us to assess trends before, after, and recovery back to pre-fire conditions. Before the fires there was very little change in fine sediment year to year. Between the first and second samples fine sediment changed by less than 1.8% at most sites. The consistency of fine sediment in the pre-fire period is due to a lack of large sediment inputs from recent floods, debris flows, or wildfires. We did not complete a sediment budget but we did make some qualitative observations of sediment sources upstream from the monitoring sites. Sediment before the fires was from long-term chronic erosion on road surfaces, from natural background sources, and from erosion of older landslide deposits stored in stream channels and floodplains.

In the year immediately after the fires, heavy precipitation on the burned area caused a very large increase in fine sediment (Figure 7). In July of 2015 the burned area experienced isolated thunderstorms with 1.19 inches of rainfall in 30 minutes. Rapid surface runoff and erosion from areas with bare, water repellent soils caused localized flooding and debris flows in Grider, Walker, Beaver, and South Russian Creeks. The flood stage in Grider Creek was magnified by a landslide dam-break flood. Fine sediment increased by 18 to 83 percent in the four streams that experienced debris flows. The largest sediment increases were in Grider and Walker Creeks where the monitoring stations were directly buried in the runout zone of debris flows. The V* measurements (upper left graph in Figure 5) show that pools in Grider Creek were completely filled with fine sediment. Other streams which had high-severity burns but did not experience debris flows had a much smaller sediment response. There was no detectable change in Elk, East Fork Elk, Kelsey, or Thompkins Creeks even though they had areas with high-severity burns. Some of these streams had a flush of very high turbidities caused by surface runoff of ash and mud, but they did not have the large increase in sediment deposition that occurred in streams with debris flows.

After a large pulse in the year immediately after the fire, fine sediment had a decreasing trend in subsequent years (Figure 7). Recovery to pre-fire sediment conditions took two years at most sites. In streams where fine sediment was above the reference condition before the fires, including Beaver and Walker Creeks, conditions returned to the same elevated levels after the fire-related sediment passed through the stream. Long-term chronic sediment sources from high road densities continue cause exceedances even after the short-term pulse of sediment from the fires routed through the stream network. In streams where fine sediment was below the reference condition before the fires, including Whites Gulch and South Russian Creek, fine sediment returned to the same low levels after a pulse of sediment from the fires passed through the stream. These watersheds have lower roaded areas than Beaver and Walker Creeks, and are more resilient to the effects of fires with a only a short-term increase above the reference.

The high sediment values from sites that were buried by debris flows in Grider and Walker Creeks plot as high outliers in the relationship between ERA and streambed sediment. Sediment at these sites are not correlated with ERA and are not predicted by the regression equations in Table 10. These results suggest that ERA is an indicator of the long-term effects of chronic erosion processes, but not the extreme short-term effects of debris flows.

Table 5. Area burned at high-severity.

Stream	High-Severity Acres
Beaver Creek 1	1,195
South Russian Creek	502
Grider Creek 1	334
Whites Gulch	240
Walker Creek 1	228

* High-severity acres are from 2014 BAER reports.

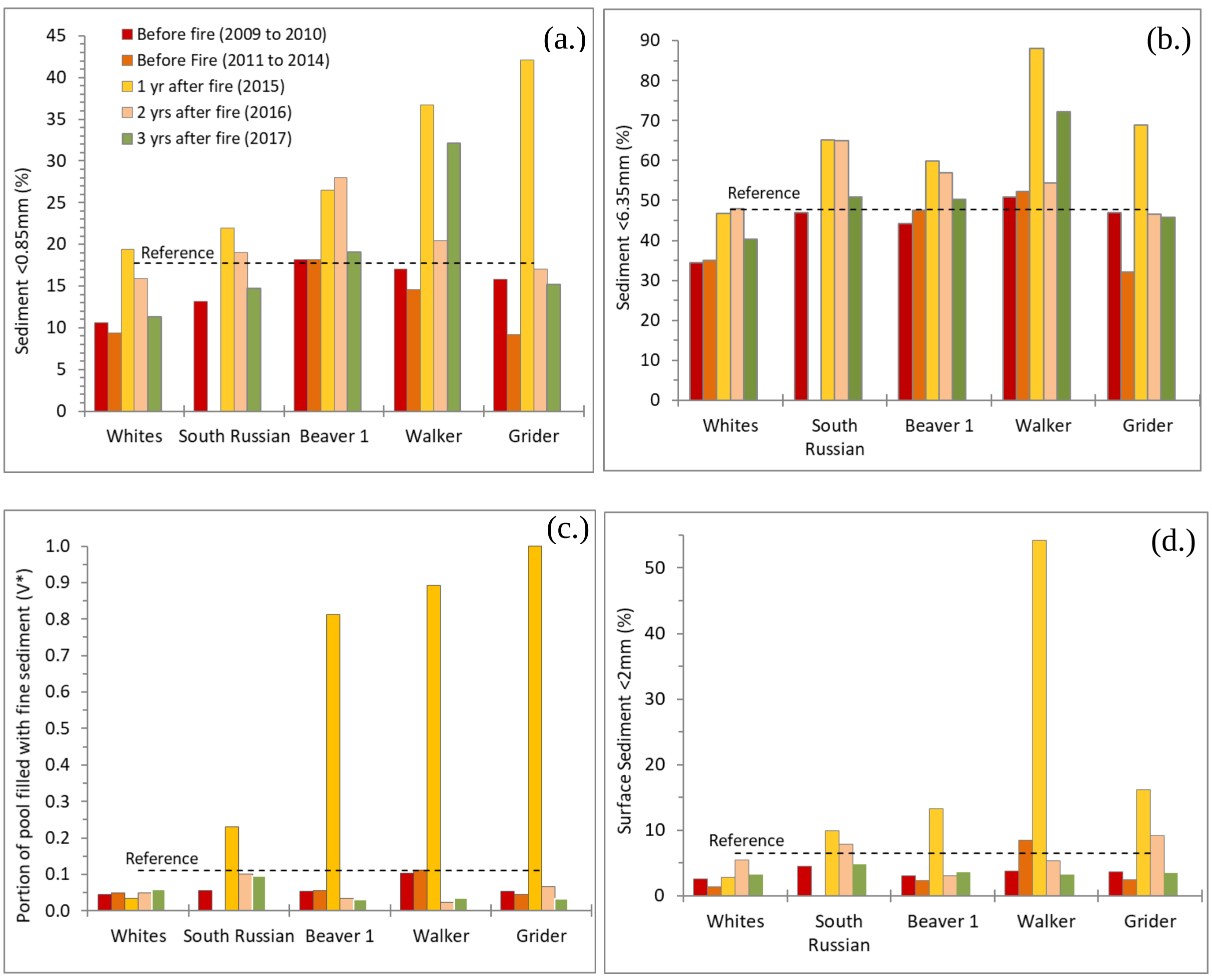


Figure 7. Trends in fine sediment in watersheds that experienced high soil burn severity in the 2014 wildfires and debris flows in 2015.

DISCUSSION and CONCLUSIONS

The Klamath National Forest developed desired conditions for in-stream fine sediment by monitoring streambed sediment in a network of reference streams. Reference streams are located in wilderness and roadless areas that represent minimally disturbed conditions as defined by Stoddard et al, (2006). The KNF reference condition is used as a benchmark to evaluate the effects of human activities and the effectiveness of Forest Service polices at maintaining or restoring water quality. The KNF reference condition represents compliance with water quality standards because natural background conditions in the absence of human impacts meets the natural condition provisions of the Clean Water Act (USEPA, 1997, 2005). The use of percentiles to identify benchmarks for attainment of water quality standards is consistent with the approach used by State and Federal regulatory agencies (EPA, 2006, 2006b). The reference condition also represents compliance with the Aquatic Conservation Strategy of the Northwest Forest Plan which requires that management actions maintain sediment conditions within the range of natural variability (USFS, 1994b). The KNF reference condition includes spatial variability due to differences in geology and other physical factors across the Forest. The reference condition also includes temporal variability due to wildfire and other disturbances but excludes recent high-severity burns that adversely affect beneficial uses.

The 33 managed watersheds in Table 3 with fine sediment less than the reference condition are fully attaining desired conditions. Fine sediment is within the natural range of variability and meets State water quality standards. However, some watersheds contain potential sediment sources on roads that have not yet delivered sediment to streams but have a high risk of triggering debris flows during floods. Road sediment sources on the KNF have been inventoried and evaluated for their risk of failure (USFS, 2012). Treatment of the highest risk sites is necessary in order to meet the TMDL sediment load reductions and prevent future increases in streambed sediment. Watersheds where the all high-risk sediment sources have been treated and in-stream sediment is less than the reference condition should be considered for removal from the Regional Water Board's 303(d) list of impaired waters.

The regressions in Table 10 provide a link between ERA and instream sediment that can be used to make predictions about the cumulative effects of forest management activities. A positive slope to the correlations indicates that increasing roaded area results in increased deposition of fine sediment on streambeds. Higher ERA is a risk to beneficial uses because other studies have shown that increasing fine sediment on streambeds is correlated with decreasing salmon egg survival (Jensen, 2009). Overall, our results are consistent with Cederholm (1980) who also found correlations between watershed roaded area and streambed sediment. Of the four sediment indicators in Table 10, the regressions for percent sediment <0.85mm should be used in effects analysis because it has a higher r^2 and strong link to aquatic life uses. Caution should be used when applying the regression models in Table 10. The models should not be used to predict an actual in-stream sediment value due to the large scatter in the data, low r^2, and wide confidence limits. ERA is a simple index of watershed disturbance that does not model all the complex watershed processes that affect in-stream sediment. Instead, ERA relies on a conceptual model of watershed processes and assumed cause and effect relationships to explain the correlation between ERA and in-stream sediment (Appendix B).

Some of the uncertainty of the ERA regression models is addressed by using confidence limits to set thresholds as shown in Figure 6. Watersheds with an ERA greater than the threshold have a 95% confidence of exceeding the natural range of sediment conditions in reference watersheds. Because the natural range of sediment conditions inherently supports aquatic life uses (USEPA, 2005), watersheds with an ERA greater than the threshold have a high risk of impacting aquatic life uses and exceeding water quality standards. The thresholds are not applicable to episodic sediment inputs from large flood events or to areas with a different geology than the KNF. The average gradient of streams in our study is 2.9%. Higher or lower gradients would affect sediment transport capacity and should be considered when applying the regressions. When applied within the limits and assumptions of the model, our results show that ERA is a valid indicator of cumulative effects of land management on in-stream beneficial uses.

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APPENDIX A - Threshold of Concern for Equivalent Roaded Area

Table A1 shows threshold of concern for ERA that is correlated with the reference condition for fine sediment at the lower 95% confidence limit. Percent sandy geology has been established for all watersheds on the KNF and is available in the appendix for KNF CWE guidebook (USFS, 2021). Percent sandy geology can be estimated for other watersheds using the criteria in Table 4.

Table A1.

Percent of Watershed with Sandy Geology	TOC for ERA (%)	Percent of Watershed with Sandy Geology	TOC for ERA (%)	Percent of Watershed with Sandy Geology	TOC for ERA (%)
0	9.1	34	7.5	68	6.3
1	9.0	35	7.5	69	6.3
2	9.0	36	7.5	70	6.2
3	8.9	37	7.4	71	6.2
4	8.9	38	7.4	72	6.2
5	8.8	39	7.4	73	6.1
6	8.8	40	7.3	74	6.1
7	8.7	41	7.3	75	6.1
8	8.7	42	7.2	76	6.1
9	8.6	43	7.2	77	6.1
10	8.6	44	7.1	78	6.1
11	8.5	45	7.1	79	6.1
12	8.5	46	7.0	80	6.1
13	8.4	47	7.0	81	6.0
14	8.4	48	7.0	82	6.0
15	8.3	49	6.9	83	6.0
16	8.3	50	6.9	84	6.0
17	8.3	51	6.9	85	6.0
18	8.2	52	6.8	86	5.9
19	8.2	53	6.8	87	5.9
20	8.1	54	6.8	88	5.9
21	8.1	55	6.7	89	5.9
22	8.0	56	6.7	90	5.9
23	8.0	57	6.7	91	5.8
24	7.9	58	6.6	92	5.8
25	7.9	59	6.6	93	5.8
26	7.9	60	6.6	94	5.8
27	7.8	61	6.5	95	5.8
28	7.8	62	6.5	96	5.8
29	7.7	63	6.5	97	5.7
30	7.7	64	6.4	98	5.7
31	7.6	65	6.4	99	5.7
32	7.6	66	6.4	100	5.7
33	7.6	67	6.3		

APPENDIX B - Conceptual Model for Equivalent Roaded Area

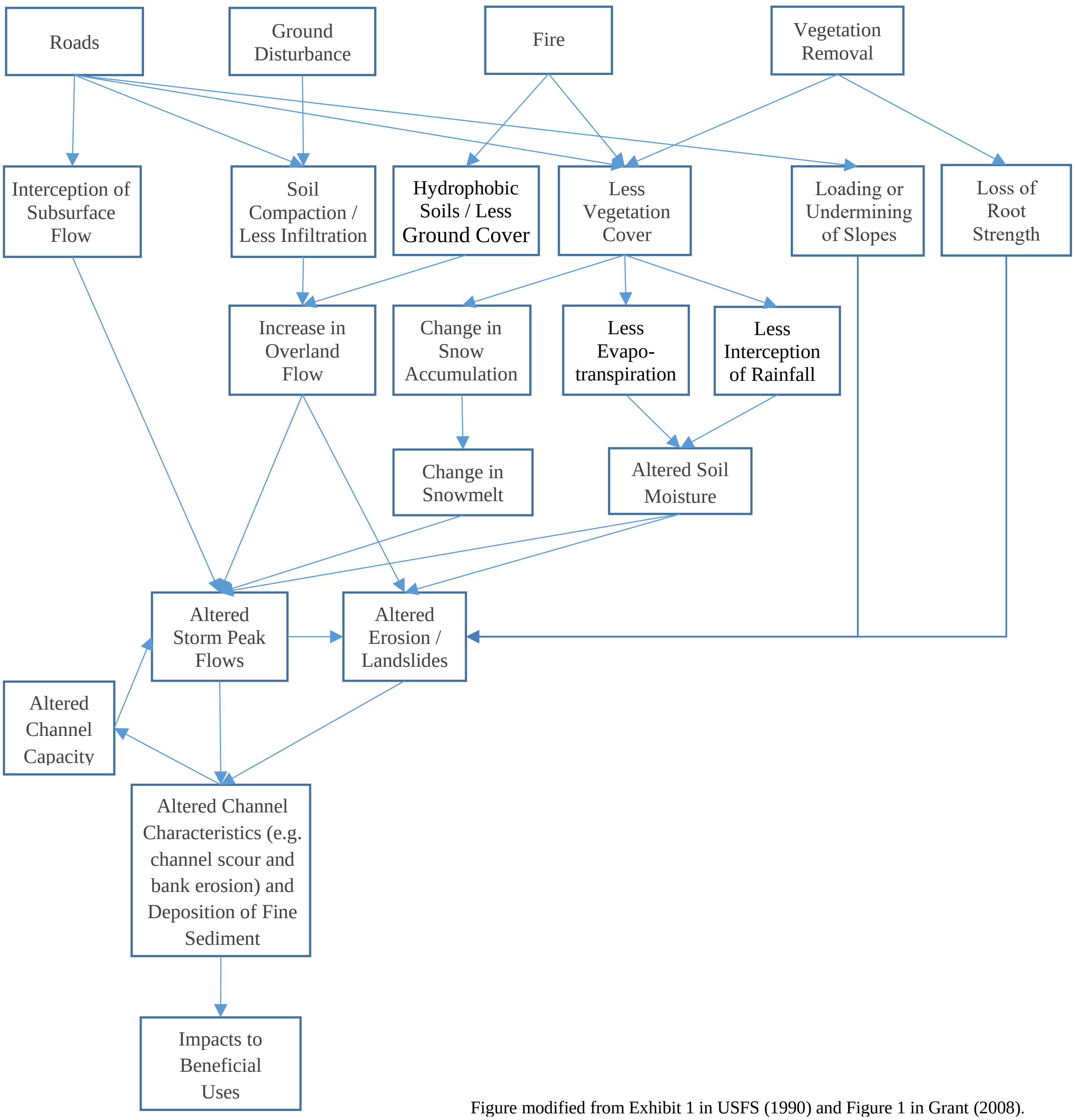

Figure modified from Exhibit 1 in USFS (1990) and Figure 1 in Grant (2008).

Figure A1. Conceptual model of cause and effect relationships between land use, climatic events, and impacts to beneficial uses. Disturbances in the top four boxes are modeled with Equivalent Roaded Area coefficients. Stream channel response in the bottom two boxes is modeled with the correlations for fine sediment. Impacts to beneficial uses is modeled with the fine sediment and salmon egg survival correlations in Jensen (2009). The processes in the middle boxes are assumed links between watershed disturbances and impacts to beneficial uses.