Anticipated Sediment Release from Klamath River Dam Removal within the Context of Basin Sediment Delivery

Final Report

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Executive Summary

Introduction

Four dams on the Klamath River owned by PacifiCorp (Iron Gate, Copco 1 and 2, and J.C. Boyle) are being considered for removal to improve fish passage and water quality. Numerical modeling under various scenarios predicted that dam removal could release up to 3.2 million tons of reservoir sediment to downstream reaches, the majority of which would be released in the first year following removal (GEC 2006, Stillwater Sciences 2008). Little sedimentation or increase in flood stage heights are expected to occur downstream of Iron Gate Dam (Stillwater Sciences 2008). Additional studies assessed the potential effects of dam removal on fish and water quality in the lower Klamath River (Stillwater Sciences 2009a, Stillwater Sciences 2009b).

This study was commissioned by the California State Coastal Conservancy to place the anticipated sediment release from dam removal into the context of background sediment delivery from watershed sources. Specific objectives of the study included (1) summarizing existing information about the quantity and size distribution of background sediment delivery from the watershed to the Klamath River, (2) comparing estimates of the cumulative background sediment delivery with independent estimates of total sediment flux, and (3) comparing modeled estimates of sediment release from dam removal with estimates of background sediment delivery.

The Klamath River traverses 254 mi and drains a 15,722 mi^2 area that includes the Modoc Plateau, Cascade Range, Klamath Mountains, and Northern Coast Range. The Klamath River watershed can be divided into upper and lower basins with distinctly different climatic, geologic, geomorphic, and hydrologic characteristics. The geologic boundary between the upper and lower basins occurs a short distance downstream of Iron Gate Dam near Cottonwood Creek. Basaltic and andesitic volcanic rocks of Cenozoic age in the Upper Klamath basin create large areas with low relief, low drainage density, little surface runoff, and low sediment delivery rates. The geologically complex Lower Klamath basin, comprised chiefly of older and more deformed metamorphic and intrusive igneous rocks, has greater relief with steeper hillslopes, a more peaked hydrologic response to storm precipitation, more active mass wasting processes, and higher sediment delivery rates.

Approach

In the absence of data characterizing the quantity and size distribution of the sediment load at key locations in the Klamath River, existing estimates of average annual sediment delivery rate from portions of the Klamath basin provide the best available means of placing the anticipated sediment release from dam removal into the context of background conditions. Sediment delivery from areas where existing information is missing or incomplete (1,330 mi^2, or 20% of the Klamath basin downstream of Iron Gate Dam) was extrapolated using sediment delivery rates reported for similar terrain types within the basin. Estimated total sediment delivery was divided into sand and coarser ($\geq$0.063 mm) and silt and finer (<0.063 mm) fractions consistent with prior studies of reservoir sedimentation, dam removal, and sediment flux in the Klamath basin. Subsurface bed material samples from previous studies of Klamath River tributaries were used as surrogates for the grain size distributions of the coarse load delivered to the mainstem Klamath River. The estimate of cumulative average annual sediment delivery ($\geq$0.063 mm) from the Klamath basin was compared to an independent estimate of total average annual sediment flux ($\geq$0.063 mm) from the Klamath River derived from discharge records.

Results

Relatively little sediment (199,300 tons y^{-1} or 3.4% of the cumulative average annual delivery from the basin) is supplied to the Klamath River in the 13.4 mi reach of the Klamath River from Keno Dam to the Shasta River. The three tributaries that contribute the largest amount of sediment to the Klamath River are the Scott River (814 mi^2 source area), Salmon River, (751 mi^2 source area) and Trinity River (2,274 mi^2 source area). The Scott River supplies 607,300 tons y^{-1} (10% of the cumulative average annual delivery from the basin), more than doubling sediment supply to the Klamath River at its confluence. The Salmon River supplies 320,600 tons y^{-1} (5.5% of the cumulative average annual delivery from the basin), increasing supply to the Klamath River by 22% at its confluence. The Trinity River supplies 3,317,300 tons y^{-1} (57% of the cumulative average annual delivery from the basin), nearly doubling sediment supply to the Klamath River at its confluence. Tributary bed material size distributions have similar geometric means, ranging from 10 to 22 mm (medium to coarse gravel). The average D84 ranges from very coarse gravel to small cobble, and the D16 ranges from very coarse sand to fine gravel. No distinct trends in tributary bed material grain size were apparent with distance downstream of Iron Gate Dam or with tributary drainage area. The estimated cumulative average annual sediment delivery in the Klamath basin (1,841,200 tons ≥0.063 mm) and the previous estimate of sediment flux from the Klamath River to the Pacific Ocean (2,502,200 tons ≥0.063 mm [Willis and Griggs 2003]) agree within 30%.

Numerical modeling predicted high, median, and low values for reservoir sediment release based on different hydrologic scenarios and assumed dimensions of the new equilibrium channel within the former impoundments (Stillwater Sciences 2008). Predicted median values of fine and total sediment load released by dam removal are significantly more (by a factor of 6 or more) than the cumulative average annual fine and total sediment delivery from the basin between Iron Gate Dam and the Scott River. Supply from the Scott River reduces the ratio of sediment load released by dam removal to annual basin sediment delivery to 2.3 (2.6 for fine load, 1.5 for coarse load). The ratio declines to 1.3 (1.5 for fine load, 0.80 for coarse load) at the Salmon River confluence and to 0.41 (0.49 for fine load, 0.25 for coarse load) at the Trinity River confluence. Predicted low values of sediment load released by dam removal are less than average annual basin sediment delivery (ratio <1.0) at the Dillon Creek River confluence for total load and the Salmon Creek confluence for fine load. Even the predicted high values of fine and total load released by dam removal are less than half the average annual fine and total load delivered from the basin (ratio <0.5) at the Trinity River confluence.

Sediment load supplied by the watershed in any given year will vary from the long-term average annual load. The highest annual sediment yield recorded in the Klamath River at Orleans (1968–1977) was three times greater than the period average, and the highest annual sediment yield recorded in the Trinity River at Hoopa (1957–1977) was 7 times greater than the period average (Janda and Nolan 1979). The *daily* suspended sediment load measured in the Klamath River at Orleans exceeded the cumulative average *annual* basin sediment delivery at the nearby Salmon River confluence on 5 days between WY 1968 and WY 1979. The highest daily suspended sediment load in the Klamath River at Orleans during the January 1974 flood was greater than the median estimate of total annual load released by dam removal. Suspended sediment flux in the Trinity River at Hoopa from December 22 to 26, 1964 was nearly 8 times the high estimate of total annual load released by dam removal.

Additional field data collection and modeling of event-based, annual, and long-term averaged transport rates by grain size fraction is needed to better understand the potential effects of sediment release from dam removal between Iron Gate Dam and the Salmon River confluence.

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1 BACKGROUND AND PURPOSE

The Klamath River traverses approximately 254 mi (409 km), originating in Upper Klamath Lake within the Cascade Mountains of Southern Oregon and flowing southwest through the Klamath Mountains and northern California Coast Range to the Pacific Ocean (Figure 1). With a watershed area of approximately 15,722 mi^2 (40,720 km^2), the Klamath River produces the second largest average annual runoff (Kruse and Scholz 2006) and sediment flux (Willis and Griggs 2003) of California's rivers. It supports several runs of anadromous fish species including Coho and Chinook salmon and steelhead trout, as well as resident rainbow and cutthroat trout. Major tributaries to the mainstem Klamath include the Williamson River and water diverted from the Lost River in southern Oregon; and the Shasta, Scott, Salmon, and Trinity rivers in northern California (Figure 1).

PacifiCorp's Klamath Hydroelectric Project annually generates approximately 716,800 megawatt-hours of electricity through operation of five dams: Keno (River Mile [RM] 233.0), J.C. Boyle (RM 224.7), Copco 1 (RM 198.6) and Copco 2 (RM 198.3), and Iron Gate (RM 190.1) (Figure 1) (FERC 2007). These dams were developed largely for hydropower generation and provide limited storage capacity, mainly in Copco 1 and Iron Gate Reservoirs. Iron Gate is the most downstream dam on the mainstem Klamath River.

Four of the dams owned by PacifiCorp on the Klamath River (Iron Gate, Copco 1 and 2, and J.C. Boyle) are being considered for removal to improve fish passage and water quality. Approximately 20.4 million cubic yards of sediment is deposited within the reservoirs impounded by these four dams (Eilers and Gubala 2003, GEC 2006). The deposits contain approximately 8.1 million tons of inorganic sediment, most of which is fine-grained (e.g., 84% of the total reservoir sediment volume is silt or finer). Proposed dam removal alternatives would result in mobilization and release of 1.4–3.2 million tons of reservoir sediment to downstream reaches, resulting in high suspended sediment loads and possibly localized short-term sediment deposition (Stillwater Sciences 2008). Because the grain size distribution of the sediment stored in the reservoirs is predominantly fine and the coarse channel bed downstream of the dams has relatively high transport capacity, concerns are primarily related to the biological impacts associated with high suspended sediment concentrations rather than downstream sedimentation that typically results from dam removal in other river systems (GEC 2006, Stillwater Sciences 2008, Stillwater Sciences 2009a).

The California State Coastal Conservancy commissioned a series of studies related to dam removal, including (1) estimation of the volume and composition of reservoir sediment deposits (Shannon and Wilson Inc. 2006, GEC 2006), (2) sediment transport modeling to evaluate potential sediment release during reservoir drawdown should the dams be removed (Stillwater Sciences 2008), (3) an analysis of potential impacts of dam removal on sensitive fish species in the lower Klamath River (Stillwater Sciences 2009a), and (4) a synthesis of previous water quality information in the Klamath River with a discussion of the potential implications of dam removal on water quality in the lower Klamath River and estuary (Stillwater Sciences 2009b). Sediment transport modeling predicted little potential for sedimentation or increases in flood stage heights resulting from sedimentation downstream of Iron Gate Dam. Based on the modeling results, the amount of pool filling is anticipated to be small and any accumulation of sediment is expected to have a short residence time. Fine sediment infiltration is expected to be limited to shallow depths near the bed surface, which would be flushed during a high flow event after the supply of fine sediment in the former reservoir area is exhausted. Coarse sediment (sand

and coarser) released by dam removal would travel slower and potentially have a longer residence time than fine sediment.

The study presented in this technical report was commissioned by the California State Coastal Conservancy to examine long-term average sediment delivery from watershed sources to reaches of the Klamath River potentially affected by sediment release from dam removal and to place the anticipated sediment release from dam removal into the context of the background sediment delivery from watershed sources.

Specific goals and objectives of the study include the following:

- Summarize existing and available information about the quantity and size distribution of sediment delivery from the Klamath basin to the Klamath River, and where information is lacking, extrapolate sediment delivery;
- Compare estimates of cumulative annual basin sediment delivery with independent estimates of total annual sediment flux from the Klamath River to the Pacific Ocean; and
- At key points along the mainstem Klamath River, compare the modeled estimates of sediment release from dam removal with estimates of background sediment delivery from the basin.

2 GEOLOGIC AND GEOMORPHIC CONTROLS ON SEDIMENT DELIVERY

The Klamath River watershed can be divided into two basins with distinctly different geologic, geomorphic, climatic, and vegetative characteristics: the Upper Klamath basin and the Lower Klamath basin. The geologic boundary between the two regions occurs a short distance downstream of Iron Gate Dam (near Cottonwood Creek). This report follows the Bureau of Reclamation (BOR) approach by referring to all areas upstream of Iron Gate Dam as the Upper Klamath basin and all areas downstream of Iron Gate Dam as the Lower Klamath basin (Figure 1). For the purpose of compiling available sediment delivery information and extrapolating available sediment delivery rates to other areas, 32 sub-basins were defined in the Lower Klamath basin (Table 1, Figure 2). Sub-basins are derived from a combination of USFS 4th or 5th field watershed boundaries used in cumulative watershed effects analysis (USDA Forest Service 2004) and from 30-m DEM data.

Table 1. Geologic terranes.

Sub-basin	Drainage area (mi^2)	Source area within geologic terrane type, mi^2							
		Igneous intrusive	Metamorphic-hard	Metasedimentary-soft	Older volcanic	Sedimentary	Unconsolidated	Younger volcanic	Total
Iron Gate Dam	8,043.6	0.4	0	0	3,971.1	472.5	1,234.5	2,113	7,791.4
Iron Gate Dam-Cottonwood	150.6	0	2.6	0	131.1	9.3	7.7	0	150.6
Cottonwood Creek	99.3	26.6	15.4	0	29.6	27.7	0	0	99.3
Cottonwood-Shasta	17.8	0.1	12.3	0	0.8	4.6	0	0	17.8
Shasta River	786.1	12.4	188.0	8.5	340.3	7.1	203.1	23.0	782.4
Humbug-Lumgrey	106.2	22.3	83.3	0.5	<0.1	<0.1	0	0	106.2
Beaver Creek	108.8	41.9	44.0	22.8	0	0.1	0	0	108.8
McKinney-Horse	154.0	31.0	57.1	65.8	0	0.1	<0.1	0	154.0
Scott River	813.6	180.1	622.7	4.0	0.1	4.1	2.5	0	813.6
Grider-Seiad	127.6	46.1	79.4	<0.1	0	2.0	<0.1	0	127.6
Thompson-China	105.0	38.6	66.1	<0.1	0	0.3	0	0	105.0
Indian Creek	134.8	31.3	103.4	0	<0.1	<0.1	0	0	134.8
Elk Creek	95.1	33.8	61.0	0	0	0.3	0	0	95.1
Clear Creek	111.4	43.0	68.4	0	0	0	0	0	111.4
Oak Flat-Ukonom	137.1	43.9	92.8	0	0	0.4	0	0	137.1
Dillon Creek	73.2	22.6	49.1	0	0	1.4	0	0	73.2
Rock-Ti	108.7	19.2	89.4	0	0	0	0	0	108.7
North Fork Salmon River	203.8	54.9	148.9	0	0	<0.1	0	0	203.8
South Fork Salmon River	290.1	59.5	217.0	0	12.1	1.4	0	0	290.1
Wooley Creek	148.6	66.9	80.8	0	0	0.9	0	0	148.6
Salmon River	108.3	31.4	77.0	0	0	<0.1	0	0	108.3
Camp Creek	42.0	0.8	41.2	0	0	0	0	0	42.0
Red Cap Creek	63.1	13.0	50.1	0	0	0	0	0	63.1
Bluff Creek	74.1	2.3	48.1	23.7	0	<0.1	0	0	74.1
Lower Middle Klamath River	94.0	3.2	85.5	5.3	0	0	0	0	94.0
Upper Trinity River	692.0	209.1	462.9	0	0.2	15.5	4.2	0	692.0
Upper Middle Trinity River	321.2	55.1	221.9	0	0	36.1	8.0	0	321.2
Lower Middle Trinity River	689.1	90.2	540.7	0	46.4	11.4	0.3	0	689.1
Hayfork Creek	385.9	95.4	207.1	0	0	81.4	1.9	0	385.9
South Fork Trinity River	545.0	41.2	143.7	104.8	0	254.6	0.6	0	545.0

Sub-basin	Drainage area (mi^2)	Source area within geologic terrane type, mi^2							
		Igneous intrusive	**Metamorphic-hard**	**Metasedimentary-soft**	**Older volcanic**	**Sedimentary**	**Unconsolidated**	**Younger volcanic**	**Total**
Lower Trinity River	333.4	88.9	186.6	19.1	0	38.9	0	0	333.4
Blue Creek	125.4	15.5	98.0	6.3	<0.1	5.6	0	0	125.4
Lower Klamath	367.0	2.1	161.9	105.2	<0.1	91.3	5.5	0	365.9
Total	15,656	1,423	4,407	366	4,532	1,067	1,468	2,136	15,399

The Klamath basin includes the Modoc Plateau, Cascade Range, Klamath Mountains, and Northern Coast Range geomorphic provinces. The Upper Klamath basin drains the Basin and Range Province, comprised predominantly of Miocene age basalts, and the Cascades Province, comprised predominantly of andesitic volcanic rocks of Cenozoic age. Miocene age basaltic volcanic rocks (and to a lesser extent lithologies of the Cascades) are highly permeable, resulting in low drainage density. Large areas with low relief are internally drained and typically filled with alluvial fan deposits and lake sediments (e.g., Klamath Marsh and Upper Klamath Lake). Tributaries in these areas exhibit very low gradient (e.g., <0.5%). The upper basin lies in the rain shadow of the Klamath and Cascade mountain ranges, and runoff is largely from relatively steady groundwater flow. Low channel gradients and limited surface runoff contribute to a muted hydrologic response to storm events and low sediment yield. There is a sharp contact between the Cascades Province and the Klamath Province along the axis of Cottonwood Creek near Hornbrook. This area includes a diversity of rock types with varying rates of sediment production and delivery.

The Lower Klamath basin occurs predominantly within the Klamath Mountains geomorphic province and is underlain by a series of geologic terranes comprised of accreted oceanic lithosphere, volcanic arcs, and mélange (Irwin 1994). The terranes were successively joined to the convergent margin of western North America through a series of accretionary episodes. Development of the Klamath Mountain terranes occurred during a sequence of tectonic episodes when continental rocks overrode the subducting oceanic plate. During each tectonic episode, new material was accreted to the existing continental margin along the subduction front. Each band of accreted material comprises a terrane and served as the backstop for the successive accretionary episode. Widespread metamorphism, folding, and faulting occurred in both the continental and accreted rocks during each episode. The complex geologic and geomorphic character of the Klamath Mountains reflects this tectonostratigraphic growth and subsequent plutonic intrusive, metamorphic, and volcanic activity that has occurred since the early Devonian (While et al. 2007).

Four primary geologic terranes (including subterranes) account for the majority of the rock exposure in the Lower Klamath basin: the Eastern Klamath terrane, the Central Metamorphic terrane, the Western Paleozoic and Triassic terrane, and the Western Klamath terrane. Rocks of the Franciscan complex (Eastern Belt and Central Belt) from the Northern Coast Range Geomorphic Province underlie a limited area of the Lower Klamath basin, including areas draining to the mainstem Klamath River downstream of Weitchpec and areas east of the South Fork Trinity in the vicinity of South Fork Mountain. The Lower Klamath basin consists chiefly of Paleozoic and Mesozoic metasedimentary and metavolcanic rocks; as well as Mesozoic and Cenozoic plutonic, volcanic, and sedimentary rocks. Rock types found in the Lower Klamath basin are correlated into seven general lithologic groups (igneous intrusive, metamorphic hard, metasedimentary soft, sedimentary, older volcanic, younger volcanic, unconsolidated) for the purpose of this study (Table 1, Figure 3). Metamorphic units of the geologic terranes account for approximately 60-70% of the rock exposed in the Lower Klamath basin. Large plutonic intrusions are also widely distributed throughout the Lower Klamath basin and account for approximately 15% of the exposed rock. Highly weathered and erodible plutonic rocks are chronic sources of sand and finer sediment to streams. To assist in relating sediment delivery rates to simplified geologic and geomorphic attributes in subbasin areas, a 30-m DEM was used to categorize hillslope gradients into four classes related to hillslope stability (0–15%, 15–35%, 35–65%, and >65%)(Figure 4).

2.1 Eastern Klamath Terrane

The Eastern Klamath Terrane was the nucleus of the Klamath Mountains during the early Devonian and served as the backstop for subsequent accretionary episodes (Irwin 1998, While et al. 2007). Rocks of the Eastern Klamath Terrane are exposed in the Upper Trinity, Shasta, and Scott River sub-basins with minor exposures in the Lower and Middle Trinity River, Iron Gate to Cottonwood, and South Fork Salmon sub-basins. In the Shasta River and Iron Gate Dam sub-basins, rocks of the Eastern Klamath Terrane are buried by Tertiary and Quaternary volcanics of the Western Cascades and High Cascades terranes. Metasediments and serpentinized ultramafics of the Yreka and Redding subterranes account for nearly 80% of the Eastern Klamath terrane rock exposure in the Lower Klamath basin. The serpentinized ultramafics form moderately steep slopes and are readily susceptible to mass wasting. The Eastern Klamath terrane occupies the eastern one-third of the Trinity River watershed and includes the Trinity ultramafic sheet, Copley greenstone, and Bragdon Formation. These units are generally considered to be more stable and erosion-resistant, with the exception of the serpentinites. The landforms, drainage patterns, and erosive characteristics of the Eastern Klamath terrane are highly variable across the study region.

2.2 Central Metamorphic Terrane

The Central Metamorphic terrane formed during the first major accretionary episode as volcanic and sedimentary oceanic crust subducted beneath the Eastern Klamath terrane. As the Eastern Klamath terrane tectonically overrode the subducting oceanic plate, metamorphism altered oceanic crust to form two medium-grade to high-grade metamorphic rock units, the Salmon Hornblende Schist and Abrams Mica Schist. Both of these units are considered moderately erodible. Undifferentiated and serpentinized peridotite is also widespread within the Central Metamorphic terrane and is susceptible to mass wasting. Significant exposures of Central Metamorphic terrane occur in the Lower and Upper Middle Trinity sub-basins with minor exposure in Iron Gate Dam to Cottonwood, Scott River, Shasta River, South Fork Salmon River, and Upper Trinity River sub-basins.

2.3 Western Paleozoic and Triassic Terrane

The Western Paleozoic and Triassic terrane underlies approximately 35% of the Lower Klamath basin area. Significant outcrops occur in all Lower Klamath sub-basins with the exception of Bluff Creek, Iron Gate Dam to Cottonwood, Lower Klamath, Upper Trinity River, and the Shasta River. The Western Paleozoic and Triassic terrane in the study area is further subdivided into the Sawyers Bar, Western Hayfork, and Rattlesnake Creek subterranes. All three subterranes contain highly variable lithology and exhibit a range of geomorphic and sediment production characteristics.

The Sawyers Bar terrane (equivalent to Eastern Hayfork & North Fork of Irwin) consists of metasediments and metavolcanics including serpentinite, gabbro, diabase, silicious tuff, chert, mafic volcanic rock, minor lenses of limestone, phyllite, and locally, pebble conglomerate. The igneous sedimentary rocks produce moderately stable slopes, while the serpentinites produce unstable slopes. The Western Hayfork terrane consists of metamorphic and metavolcanic rocks that form relatively steep, stable slopes. These rocks are less prone to mass wasting and landslides are a relatively minor feature in this terrane (USDA Forest Service 2003). The Rattlesnake Creek terrane is composed of a mixture of metamorphic rocks including ultramafics, gabbro, volcanics, phyllite, limestone, and locally, sandstone and pebble conglomerate. This unit is highly deformed and is generally considered unstable, with numerous landslide features.

2.4 Western Klamath Terrane

The Western Klamath terrane occurs along the western margin of the Klamath Mountains. Sub-basins with significant exposures include Blue Creek, Bluff Creek, Camp Creek, Clear Creek, Lower Middle Klamath, Lower Trinity, Red Cap Creek, Rock-Ti, and the South Fork Trinity River. The Western Klamath terrane consists chiefly of metasedimentary rock (approximately 77%) and minor amounts of serpentinite and serpentinized ultramafics, metavolcanics, and low to medium-grade metamorphic rocks formed along contacts and structural boundaries. The Western Klamath terrane includes the Galice and Rogue Formations (interbedded graywacke, mudstone, conglomerate, and some volcanic rocks). Galice metavolcanic rocks generally form steep slopes and are less susceptible to mass wasting with fewer occurrences of landslide features than Galice metasedimentary rocks. Debris slides occur within Galice along the South Fork Trinity, where the river parallels the strike of South Fork Mountain and dip-slopes are formed. The Galice has moderately stable slopes where the mainstem Trinity River crosses the terrane.

2.5 Franciscan Complex

The Franciscan Complex of upper Jurassic through Cretaceous age was deposited in a deep marine trench on oceanic crustal basement and subsequently accreted to North America, uplifted, and deformed. Rocks of the Franciscan Complex vary greatly in lithology, structure, and degree of metamorphism. The Franciscan Complex is subdivided into the Eastern, Central, and Coastal belts that young from east to west. Rocks of the Eastern and Central belts occupy a relatively small area in the Lower Klamath basin, primarily in the South Fork Trinity, Lower Klamath, Bluff Creek, and Blue Creek subbasins with minor occurrences in the Lower Trinity and Lower Middle Klamath subbasins. Exposures consist primarily of the South Fork Mountain Schist, Broken Formation, mélange, and undifferentiated metasediments and metavolcanics. Schistose metasedimentary and metavolcanic rocks in the Eastern belt that are highly sheared, folded, and metamorphosed are weakly resistant to weathering and commonly form slopes with broad curvature and a thick colluvial soil mantle. Mélange in the Central belt is characterized by hummocky topography with grassland or brush vegetation cover, commonly fails in large earthflows or by debris slides on steep slopes, and is susceptible to gully erosion.

3 EXISTING INFORMATION ABOUT SEDIMENT DELIVERY

Sediment delivery has been estimated for portions of the Klamath basin through various methods, including field inventory of sediment sources, interpretation of air photos and other historical information, estimation of reservoir sediment accumulation, and modeling based on empirical sediment delivery rates for specific geomorphic terrains. Existing estimates of sediment delivery and the terrain characteristics in the respective source areas provide the best available means of extrapolating sediment delivery throughout the Lower Klamath basin. Primary sources of existing information about sediment delivery to the Klamath basin include the following (Figure 2):

1. Assessment of the quantity and characteristics of sediment stored in Iron Gate, Copco 2, and J.C. Boyle reservoirs (GEC 2006);
2. The sediment budget developed by PacifiCorp and submitted to FERC as part of the final license application for the Klamath Hydroelectric Project (FERC No. 2082) (PacifiCorp 2004);

3. Sediment source inventories conducted in support of sediment TMDLs in the Scott River, Trinity River, and South Fork Trinity River sub-basins (EPA 1998, 2001; NCRWQCB 2005);
4. Cumulative watershed effects analyses and watershed analyses conducted for federal lands administered by the Forest Service (UDSA Forest Service 2003, 2004, 2005; Elder 2005, 2006); and
5. Sediment source inventories conducted on industrial timberlands (Simpson Resource Company 2002).

In using these various sources of information to estimate cumulative average annual sediment delivery to the Klamath River, one must consider uncertainties related to (1) differences in the treatment of erosion and transport processes influencing sediment delivery, (2) differences in measurement and computation methods employed at different spatial scales, and (3) differences in the period of record over which sediment delivery is estimated. Nonetheless, these data sources provide the best available means of estimating background sediment delivery within the large Klamath basin and placing the predicted sediment release from dam removal into the context of background conditions. The estimate of cumulative average annual sediment delivery from the Klamath basin is compared to an independent estimate of total average annual sediment flux from the Klamath River to the ocean based on analysis of long term water and sediment discharge records at gaging stations (CDBW and SCC 2002, Willis and Griggs 2003).

3.1 Klamath River Dam and Sediment Investigation

The State Coastal Conservancy and the Ocean Protection Council commissioned a study to characterize sediment behind four dams on the Klamath River (Iron Gate, Copco 2, Copco 1 and J.C. Boyle) and examine sediment management issues related to dam removal (GEC 2006). The volume of sediment accumulated in each impoundment since dam construction was determined as the difference between two area capacity curves, one developed from topography prior to sediment filling and the other developed from bathymetry surveyed in 2001 (Eilers and Gubala 2003, GEC 2006). Sediment borings and grab samples were taken at 26 locations in three reservoirs. The analysis indicated that approximately 20,400,000 yd^3 of sediment is trapped in three of the reservoirs (Iron Gate, Copco 1 and J.C. Boyle), of which 84% is silt or finer (Table 2) (GEC 2006). Copco 2 is a small reservoir with no significant sediment deposit. Stillwater Sciences (2008) converted the sediment volumes into masses based on laboratory analysis of sediment samples (Table 2). The total average annual sedimentation rate in the three reservoirs is approximately 151,000 tons yr^{-1} (213 tons mi^{-2} yr^{-1}).

Table 2. Sedimentation rates in Iron Gate, Copco 2, and J.C. Boyle Reservoirs (GEC 2006, Stillwater Sciences 2008)

Reservoir	Source area, mi^2	Period of sediment accumulation	Sediment accumulation		Sedimentation rate, tons yr^{-1}
			Volume[1], yd^3	Mass[2], tons	
Iron Gate	212	40 yr (1962–2002)	8,881,000	3,950,000	98,750
Copco 1	273	84 yr (1918–2002)	10,879,000	3,871000	46,083
J.C. Boyle	225	44 yr (1958–2002)	635,000	283,000	6,432
Total			20,396,000	8,104,000	151,000

[1] GEC (2006)

[2] Stillwater Sciences (2008)

3.2 Sediment Budget for the Upper Klamath Basin

A sediment budget was developed for portions of the upper and lower Klamath River as part of a suite of water resources studies prepared in support of a license application for PacifiCorp's Klamath Hydroelectric Project (FERC No. 2082) (PacifiCorp 2004, 2005). The PacifiCorp sediment budget describes sediment production and routing through reservoirs and river reaches from Link River Dam in Oregon (RM 254.5)[1] to approximately Seiad Creek in California (RM 130). The sediment budget incorporates various measurements and observations, including analysis of mass wasting from aerial photographs, delta sedimentation rates, existing estimates of sediment delivery rates, and bedload transport rates.

Sediment delivery rates included in the PacifiCorp sediment budget were estimated using three key sources of information: (1) analyses of sediment yield from the major tributaries entering Iron Gate Reservoir based on delta sedimentation rates, (2) mapping of discrete sediment sources, and (3) extrapolation of published sediment delivery rates typical of the Klamath Mountains. The three major tributaries entering Iron Gate Reservoir (Scotch, Camp/Dutch, and Jenny Creeks) are sourced entirely within Cascades volcanic terrane, and delta sedimentation rates in these reservoir arms were used to estimate sediment yield (i.e., sediment delivery rate) from Cascades terrane. Sedimentation rates in these tributary deltas of the reservoir were determined by mapping and surveying delta deposits, computing the net change in sediment volume relative to pre-dam topography, and dividing the volume by the source area and time since closure (GMA 2004). Delta surveys indicated long term sediment yield from Iron Gate tributaries was in the range of 150–190 tons mi^{-2} yr^{-1}. Estimated sediment delivery rate derived from sedimentation rates was increased by 20% to account for transport of fine-grained sediment beyond the delta deposits. A unit-area sediment yield of 192 tons mi^{-2} yr^{-1} was used by PacifiCorp to extrapolate sediment delivery from sources areas between Link River Dam and the Cottonwood Creek confluence. Estimated sediment delivery from tributaries was weighted by a connectivity factor (high [1.0], medium [0.5], or low [0.25]) based on slope, presence of depositional zones in upstream reaches, and presence of depositional zones prior to entering the mainstem. Point sources from mass wasting that delivered sediment directly to the Klamath River were mapped in the J.C. Boyle bypass reach and other select reaches. Sediment delivery from all source areas between Cottonwood Creek and approximately Seiad Creek were estimated based on a single average annual sediment delivery rate from the Salmon River basin (450 tons mi^{-2} yr^{-1}) reported in the Salmon Sub-basin Sediment Analysis (Fuente and Haessig 1993). Results of the PacifiCorp sediment budget estimate long-term, average annual sediment delivery and do not account for differences among bed load, suspended load, and wash load.

The PacifiCorp sediment budget estimated a cumulative average annual sediment delivery rate of approximately 40,300 t yr^{-1} to channel reaches and reservoirs between Keno Dam and Iron Gate Dam (Table 3) (PacifiCorp 2005). The cumulative average annual total sediment delivery estimated by PacifiCorp is about 27% of the average annual total sedimentation rate (151,000 tons yr^{-1}) in the Iron Gate, Copco 1, and J.C. Boyle impoundments (GEC 2006). The large discrepancy results primarily from the connectivity factors that were applied to estimates of sediment delivery in the sediment budget, which typically reduce sediment delivery from tributaries by a factor of 0.25–0.5 below the rate required to balance reservoir sedimentation. The discrepancy may, to a lesser degree, be related to measurement errors and uncertainties in estimates of delta sediment volume and total reservoir sediment volume, which were determined by different investigators using different methods. Analysis of cumulative average annual

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[1] River miles reported herein are derived from a recent high resolution streamline and may vary from those reported in the PacifiCorp sediment budget.

sediment delivery herein uses an average sediment delivery rate of 151,000 tons yr^{-1} calculated from reservoir sediment volumes reported in GEC 2006 (Table 2) and consistent with that used as the basis for modeling reservoir sediment volumes potentially released by dam removal (Stillwater Sciences 2008).

Table 3. Sediment delivery estimated in the sediment budget prepared for the Klamath Hydroelectric Project (PacifiCorp 2005).

Reach				Source area (mi^2)		Sediment delivery ($\mathrm{t\ yr}^{-1}$)	
From	**RM**	**To**	**RM**	**Incremental**	**Cumulative**	**Incremental**	**Cumulative**
Link River Dam	254.5	Keno Dam	253.0	110	110	211	211
Keno Dam	253.0	JC Boyle Dam	224.6	160	270	7,668	7,879
JC Boyle Dam	224.6	Copco Dam	198.9	225	495	19,271	27,150
Copco Dam	198.9	Iron Gate Dam	179.4	273	767	13,403	40,553
Iron Gate Dam	179.4	Cottonwood Creek	182.1	212	979	66,262	106,815
Cottonwood Creek	182.1	Shasta River	176.7	793	1,772	356,783	463,598
Shasta River	176.7	Beaver Creek	161.0	416	2,188	188,614	652,212
Beaver Creek	161.0	Horse Creek	147.3	61	2,249	27,388	679,600
Horse Creek	147.3	Scott River	143.0	813	3,062	366,055	1,045,655
Scott River	143.0	Seiad Creek	130.0	72	3,135	32,428	1,078,083

PacifiCorp estimated that an additional 1,037,500 t yr^{-1} is delivered to the Lower Klamath River between Iron Gate Dam and approximately Seiad Creek. Estimates of sediment delivery to the Lower Klamath River downstream of Iron Canyon Dam are refined herein using terrain-specific delivery rates and more site-specific sources of sediment delivery information.

3.3 Sediment TMDLs for Lower Klamath Sub-basins

The Scott River, mainstem Trinity River, South Fork Trinity River, and Klamath River downstream of the Trinity River confluence at Weitchpec are listed as sediment impaired under Section 303(d) of the federal Clean Water Act. Sediment source analyses, total maximum daily load (TMDL) allocations for sediment, and sediment TMDL implementation plans have been completed for the Scott River, Trinity River, and South Fork Trinity River basins. A sediment source analysis and sediment TMDL have not been completed for the Klamath River downstream of the Trinity River confluence. The North Coast Regional Water Quality Control Board (NCRWQCB) adopted a regional sediment TMDL implementation policy for the Klamath River downstream of the Trinity River (Resolution R1-2004-0087 on 29 November 2004), and no additional sediment sources analyses are scheduled to be conducted in the basin.

3.3.1 Scott River sub-basin

Scott River drains 813 mi^2, approximately 12% of the Klamath basin area downstream of Iron Gate Dam. The State of California identified the Scott River as a sediment-impaired water body in accordance with 303(d) of the Clean Water Act and initiated efforts to recover beneficial uses of water through the TMDL process. During development of the TMDL, the NCRWQCB subdivided the watershed into seven sub-watersheds: East Headwater, West Headwater, Eastside, Scott Valley, Westside, East Canyon, and West Canyon. A sediment source assessment conducted as part of the TMDL process identified sediment sources in Scott River sub-watersheds and estimated delivery from those sources (NCRWQCB 2005). The sediment source inventory considered sediment delivery from roads, shallow landslides, streamside mass wasting, and soil creep. A combination of methods were used to estimate sediment production and delivery, including existing inventories, limited field sampling, aerial photographic interpretation, modeling, and extrapolation of empirical values to similar geologic terranes. Bedrock geology in the Scott River basin is highly variable. The NCRWQCB sampled sediment sources within four generalized bedrock strata: granitic (10.6% of watershed), mafic and ultramafic (16.8% of watershed), sedimentary and metamorphic (62.8% of watershed), and Quaternary deposits (9.8% of watershed).

The results of the sediment source analysis for the Scott River basin indicated that natural processes deliver 364,200 t yr^{-1} of sediment, while management-related sources deliver about 243,900 t yr^{-1} (Table 4). Total sediment delivery is estimated to be approximately 608,100 t yr^{-1}. Natural sediment sources are primarily associated with streamside landslides, bank erosion, and gullying. The largest anthropogenic sediment sources include road-related landslides and stream crossing failures. Sediment delivery estimated in the TMDL is substantially more than sediment delivery estimated in the PacifiCorp sediment budget. The TMDL estimates of sediment delivery were based on field sampling of sediment sources and delivery at multiple sites within the Scott River basin stratified by geologic terrane, whereas the estimates of sediment delivery in PacifiCorps sediment budget were based on extrapolation of a single rate from the Salmon River basin. The analysis of cumulative sediment delivery in the Klamath basin herein incorporates the more spatially explicit and terrain-specific sediment delivery estimates from the Scott River sediment TMDL.

Table 4. Estimates of sediment delivery from the Scott River sub-basin (NCRWQCB 2005).

Subwatershed	Source area (mi^2)	Sediment delivery (tons yr^{-1})		
		Background	Management	Total
West Canyon	99	53,856	48,213	102,069
East Canyon	100	51,100	24,200	75,300
Eastside	121	59,411	26,378	85,789
East Headwaters	115	43,355	36,110	79,465
West Headwaters	44	26,488	15,092	41,580
Westside	179	92,722	48,151	140,873
Scott Valley	156	37,284	45,708	82,992
Total	814	364,216	243,852	608,068

3.3.2 Mainstem and South Fork Trinity River sub-basins

The Trinity River sub-basin drains 2,967 mi^2, or approximately 44% of the Klamath basin area downstream of Iron Gate Dam. The Trinity River joins the Klamath River at Weitchpec, located 43 miles upstream of the Klamath River mouth. The South Fork Trinity River originates in the North Yolla Bolly Mountains and flows northwest for approximately 90 miles before reaching the confluence with the mainstem Trinity River near Salyer. The South Fork Trinity River drains 932 mi^2 (14% of the Klamath basin area downstream of Iron Gate Dam), and the mainstem Trinity

River drains 2,035 mi^2 (30% of the Klamath basin area downstream of Iron Gate Dam). Elevations range from over 9,000 ft in the Trinity Alps to less than 300 ft at the confluence with the Klamath River. The majority of the basin is under public ownership. The Hoopa Tribe occupies 144 mi^2 of the lower basin. The majority of the mainstem Trinity River basin lies within the Klamath Mountains Geomorphic Province. The South Fork Trinity River basin straddles the boundary between the Klamath Mountains and the Coast Ranges geomorphic provinces. Geologic units in the Klamath Mountains province within the Trinity River basin include the Galice Formation, Rattlesnake Creek Terrane and the Hayfork Terrane (which includes scattered granitic and ultramafic intrusions). Geologic units in the less stable Coast Range Province within the Trinity River basin include the highly erodible South Fork Mountain Schist.

The State of California identified the Trinity River and South Fork Trinity River basins as sediment impaired water bodies in accordance with 303(d) of the Clean Water Act. The EPA completed sediment TMDLs for the South Fork Trinity River in 1998 (EPA 1998) and for the remainder of the Trinity River basin (excluding tribal lands) in 2001 (EPA 2001). The mainstem Trinity River basin was divided into four subwatersheds: the Upper Mainstem Trinity River upstream of Trinity Dam, Upper Middle Trinity River, Lower Middle Trinity River, and Lower Trinity river. The South Fork Trinity River basin was divided into three subwatersheds: the upper South Fork from the headwaters to its confluence with Hayfork Creek, the lower South Fork from the Hayfork Creek to the mainstem Trinity River, and the Hayfork Creek sub-basin. Sediment source assessments conducted as part of the TMDLs identified sediment sources and estimated delivery from those sources from 1944 to 1990 in the South Fork Trinity River (Raines 1998) and from 1924 to 2000 in the mainstem Trinity River basin (GMA 2001a). The sediment source inventories considered sediment delivery from background and management-related landsliding, fluvial erosion (gullies, rilling, and bank erosion), surface erosion from roads and harvest areas, and erosion from legacy mining. A combination of methods were used to estimate sediment production and delivery, including existing inventories, limited field sampling, aerial photographic interpretation, modeling, and extrapolation of empirical values to similar geologic terranes. For the mainstem Trinity River basin, existing sediment transport records were compiled and additional sediment transport and turbidity data were collected at synoptic sites during WY 2000 and WR 2001 (GMA 2001a). These data were used to compute transport rates by grain size (>8 mm or <8 mm), tributary sediment loads, and a sediment budget for the mainstem Trinity River.

The results of the sediment TMDLs for the Trinity River basin indicated that natural processes deliver 2,081,100 t yr^{-1}, while management-related sources delivery about 1,236,300 t yr^{-1} (Table 5). Total sediment delivery is approximately 3,317,300 t yr^{-1} (1,460 t $mi^{-2}yr^{-1}$). These rates exclude sediment sources from the Upper Trinity River subwatershed that are trapped in Claire Engle Reservoir. Most active landsliding occurs as shallow debris slides in the structurally weak Galice Formation. Deep-seated landslides are common in the Rattlesnake Creek Terrane and the South Fork Mountain Schist.

Table 5. Estimates of sediment delivery from the Trinity River and South Fork Trinity River sub-basins (EPA 1998, 2001).

Subwatershed	Source area (mi^2)	Sediment delivery (tons yr^{-1})		
		Background	Management	Total
Upper Mainstem Trinity	692	798,798	360,324	1,159,122
Upper Middle Trinity	321	184,254	243,318	427,572
Lower Middle Trinity	720	815,307	194,292	1,009,599
Lower Trinity	303	446,007	452,374	898,382
Upper South Fork Trinity	343	239,039	121,033	360,072
Lower South Fork Trinity	202	328,171	153,596	481,767
Hayfork Creek	387	68,296	71,647	139,943
Total[1]	2,276	2,081,074	1,236,260	3,317,334

[1] Total excludes upper mainstem Trinity subwatershed upstream of Trinity Dam.

3.4 Cumulative Watershed Effects Analyses and Watershed Analyses for Public Lands Administered by the USDA Forest Service

The majority of the Lower Klamath basin encompasses public lands administered by the Klamath, Shasta-Trinity, and Six Rivers National Forests. The USDA Forest Service addresses erosion processes and sediment delivery during cumulative watershed effects (CWE) analysis and watershed analysis. Results from these analyses provide an important basis for estimating average annual sediment delivery to the Klamath River.

3.4.1 Cumulative watershed effects analyses on Klamath and Shasta-Trinity National Forests

The Klamath National Forest estimated sediment delivery on the west side of the Klamath National Forest in 1998 as part of a cumulative watershed effects (CWE) assessment. Sediment delivery from 7th field watersheds was estimated using two spatially explicit models that predict sediment delivery to streams from mass wasting (the GEO model) and from surface erosion (the Universal Soil Loss Equation [USLE])(UDSA Forest Service 2004, 2005). The GEO model accounts for the influence of geomorphic terrains, roads, timber harvest activity, and recent wildfires on sediment delivery from mass wasting by assigning a matrix of empirically defined sediment delivery coefficients in a Geographic Information System (GIS). The GEO modeling approach, based largely on detailed geomorphic terrain mapping and associated empirical rates of sediment delivery from those terrains, allows for a spatially explicit, process-based approach to estimating sediment delivery. The approach was initially calibrated using sediment delivery coefficients developed in the Salmon Sub-basin Sediment Analysis (Fuente and Haessig 1993) in which information on topography, geomorphic terrains, land use, and other disturbances were used with measured historical sediment delivery rates from mass wasting to predict future sediment delivery under different management conditions. The sediment delivery coefficients applied to geomorphic terrain units have subsequently been updated and modified based on sediment source inventories in the Klamath and Shasta-Trinity National Forests. The USLE model, modified by the Klamath National Forest (KUSLE), predicts sediment delivery to streams from "soil loss" based on rainfall runoff, slope length and steepness, cover, soil erodibility, and delivery factors. These models have been refined since 1998 and applied to site-specific, project-scale CWE assessments.

The Klamath National Forest updated the 1998 assessment with a CWE analysis of all Klamath National Forest lands in 2004 (UDSA Forest Service 2004). The 2004 analysis area consisted of 409 7th-field drainages, 330 on the west side of Klamath National Forest (extending downstream to the Salmon River confluence) and 79 on the east side. Estimates of sediment delivery from the 2004 CWE analysis encompassed 3,012 mi^2 (44.9 % of the Lower Klamath basin downstream of Iron Gate Dam), including all source area between the Salmon River and the Scott River. The assessment, however, included only portions of the source area in the Scott River basin (605.1 mi^2 or 74% of the Scott River basin), the Shasta River basin (243.9 mi^2 or 31% of the Shasta River basin), and the area draining to the Klamath River between Cottonwood Creek and Iron Gate Dam (51.6 mi^2 or 34% of the source area from Cottonwood Creek to Iron Gate Dam). Sediment delivery from the remaining source areas in these subwatershed areas is estimated herein by extrapolating sediment delivery rates predicted by the 2004 CWE analysis and other published sediment delivery rates in nearby areas with similar terrain characteristics (refer to Section 5.1 below). The 2004 CWE model analysis differed from that in 1998 in that it included activities on private lands in Beaver Creek, Horse Creek, Doggett Creek, and portions of Scott River; different recovery curves were used for vegetative disturbances (fire and timber harvest activities); roads were modeled differently depending on status, road surface width, road surfacing material, template, and use; GEO model coefficients were modified to reflect information from the 1997 Flood assessment and the effects of side-slopes on road prism widths; and the delivery factor for the USLE model was increased (USDA Forest Service 2004). Table 6 summarizes estimates of sediment delivery from the Lower Klamath basin reported in the 2004 CWE analysis (USDA Forest Service 2004).

Table 6. Estimates of sediment delivery from Klamath National Forest lands in the Lower Klamath basin from cumulative watershed effects analysis (USDA Forest Service 2004).

Subwatershed	Source area (mi^2)	Sediment delivery	
		$t\ yr^{-1}$	$t\ mi^{-2}\ yr^{-1}$
Bogus-Willow	52	3,421	66
Cottonwood Creek	99	14,600	147
Shasta River	243	14,621	60
Humbug-Lumgrey	106	32,451	306
Beaver Creek	109	71,210	654
Scott River	605	191,575	317
McKinney-Horse	154	93,204	605
Grider-Seiad	128	68,467	536
Thompson-China	105	51,075	487
Indian Creek	135	73,311	544
Elk Creek	95	38,685	407
Clear Creek	111	42,041	377
Oak Flat-Ukonom	137	72,370	527
Dillon Creek	73	28,418	388
Rock-Ti	109	85,523	788
Salmon River	751	320,622	427
Total	3,012	1,201,593	399

Estimates of sediment delivery from the 2004 CWE analysis do not account for sediment delivery associated with the large fires that occurred in the Lower Klamath basin in 2006 and again in 2008. Recovery rates applied to burned areas and harvested areas in the 2004 CWE analysis underestimate the effects of burns and timber harvest since 2004 (D. Elder, USDA Forest Service, pers. comm. with J. Stallman, February 2010). Estimates of sediment delivery do not account for road improvements, decommissioning, or other changes that reduce sediment delivery from the road network. Since 2004, CWE analyses have been conducted at finer resolutions for Beaver Creek as part of the Mt. Ashland Late-Successional Reserve Habitat Restoration and Fuels Reduction Project (Elder 2006) and for Horse Creek as part of the Horse Heli Project (Elder 2005) The CWE analyses do not account for natural hydrologic disconnection that may limit sediment delivery to the Klamath River, particularly in the Bogus-Willow and Shasta watershed areas that drain High Cascades terrane in the vicinity of the Shasta Valley.

3.4.2 Watershed analysis on Six Rivers National Forest

As part of the Lower Middle Klamath Watershed Analysis, Six Rivers National Forest estimated sediment delivery from mass wasting in portions of the Lower-Middle Klamath sub-basin area between the Salmon River confluence near Sommes Bar and the Trinity River confluence near Weitchpec (USDA Forest Service 2003). The analysis area included approximately 94 mi^2 (1.4 % of the Lower Klamath basin downstream of Iron Gate Dam) in the Orleans Ranger District. The watershed analysis excluded the three largest tributaries in this reach of the Klamath River: Bluff Creek, Camp Creek, and Red Cap Creek. The analysis area is underlain predominantly by metasedimentary and metavolcanic rocks of the Galice Formation (53%), metasedimentary rocks of the Western Hayfork Terrane (22%), and serpentinitic volcanic sediments (melange) of the Rattlesnake Creek Terrane (5%). The remaining area is underlain by South Fork Mountain schist (5%), dioritic to ultramafic igneous bodies (11%), and surficial deposits. Sediment delivery from mass wasting was estimated from an aerial photographic inventory of historically active landslides and from data relating landslide areas to volumes in similar terrain (USDA Forest Service 2003). Six Rivers National Forest estimated sediment delivery by subwatershed (Table 7) and by geologic unit (Table 8). Average annual sediment delivery during the period 1944–1998 was 85,600 t y^{-1} (912 t mi^{-2} y^{-1}) (USDA Forest Service 2003).

Table 7. Estimates of sediment delivery from sub-watersheds included in the Lower-Middle Klamath Watershed Analysis.

Subwatershed	Source area (mi^2)	Sediment delivery (1944–1998)	
		t y^{-1}	t mi^{-2} y^{-1}
Aikens	4.0	3,702	938
Boise	15.6	5,738	368
Cavanaugh	10.3	10,962	1,063
Crawford	6.1	9,342	1,528
Hopkins	9.0	10,231	1,137
Ikes	14.0	9,171	657
Pearch	6.6	2,222	339
Red Cap Gulch	7.9	10,138	1,279
Slate	13.7	12,667	927
Whitney's Gulch	6.8	11,420	1,682
Total	93.9	85,593	912

Table 8. Estimates of sediment delivery from geologic terranes within the Lower-Middle Klamath Watershed Analysis area.

Geologic unit	Source area (mi^2)	Sediment delivery (1944–1998)		
		tons	$t\ y^{-1}$	$t\ mi^{-2}\ y^{-1}$
Galice metasedimentary	40.4	2,840,800	51,651	1,280
Galice metavolcanic	12.4	962,700	17,504	1,410
Hayfork Terrane	20.1	228,900	4,162	207
Rattlesnake Ck Terrane	4.7	59,800	1,087	232
Mesozoic intrusive	10.2	560,800	10,196	1,003
Schist	6.1	105,800	1,924	314

Approximately 60% of the sediment delivery originated from Galice metasediments or older deep-seated landslides within that unit, while approximately 20% originated from Galice metavolcanics. Surface erosion was primarily associated with gullying in finer-grained lithologies (e.g., South Fork Mountain schist, Galice slate and phyllite, Rattlesnake Creek Terrane) and shear zones, steeper slopes on coarser-grained igneous and sedimentary rocks (especially in the Western Hayfork Terrane), landslide scars, areas recently burned by intense wildfire, and clear-cut areas. Estimates are considered accurate to within ±30% (USDA Forest Service 2003).

3.5 Sediment Delivery from Private Timberlands in the Lower Klamath Basin

Simpson Resource Company (hereafter referred to as Green Diamond [GD]) estimated sediment delivery within their Habitat Conservation Plan (HCP) area by constructing an empirical model designed to evaluate long-term average annual sediment delivery from mass wasting (road-related and non-road-related) under different management scenarios (Simpson Resource Company 2002). The primary data sources used to parameterize sediment delivery rates were landslide inventories (in three watersheds) and road erosion inventories (in five watersheds) conducted on GD ownership. Inventories of mass wasting and road erosion were conducted in Hunter Creek (15.8 mi^2), the most downstream subwatershed in the Lower Klamath basin. The Hunter Creek watershed is in the Coast Range Geomorphic Province and is underlain predominantly by the Broken Formation of the Eastern Belt Franciscan Complex. Inventories of sediment delivery in Hunter Creek provide unit area sediment delivery rates for Coast Range terrane that can be extrapolated to other similar areas of the Lower Klamath sub-basin where no other sources of sediment delivery information have been identified, including most of the source area from the Trinity River confluence to the mouth of the Klamath River.

Sediment delivery from open slope and road-related shallow landslides (i.e., debris slides, debris flows, and streamside failures) were calculated from field inventory data and/or estimated from aerial photographic interpretation (Simpson Resource Company 2002). Sediment delivery from active and dormant deep-seated landslides was estimated based on the length of stream intersection, average depth of failure, and average movement rate. Background sources delivered approximately 2,847 $t\ yr^{-1}$ and management-related sources delivered approximately 9,383 $t\ yr^{-1}$ of sediment to Hunter Creek (using a density of 1.5 tons yd^{-3}). Total average annual sediment delivery was estimated to be 12,230 $t\ yr^{-1}$ (773 $t\ mi^{-2}\ yr^{-1}$).

4 EXISTING INFORMATION ABOUT THE GRAIN SIZE DISTRIBUTION OF SEDIMENT DELIVERY

4.1 Fractionation of Coarse and Fine Load

Determining the coarse and fine fractions of the total sediment load requires long-term sampling of the quantity and size distribution of bedload and suspended load material over a wide range of flows that transport sediment. In the Klamath basin, bedload and suspended load have not been sampled at sufficient spatial or temporal scales necessary to empirically determine the quantity and size distribution of the coarse and fine fractions. In the absence of these data, total sediment delivery in this study was broken into two general grain size classes: sand and coarser (≥0.063 mm) and silt and finer (≤0.063 mm). This break in grain size is consistent with that used in prior studies related to reservoir sedimentation and dam removal in the Klamath basin (Shannon and Wilson Inc. 2006; GEC 2006; Stillwater Sciences 2008, 2009a, 2009b) and is consistent with analysis of the potential effects of dams at reducing coarse sediment supply to California beaches (CDBW and SCC 2002, Willis and Griggs 2003). Upstream of Cottonwood Creek, calculation of fractional sediment delivery assumes that 16% of the total load is sand and coarser based on the grains size distribution of sediment deposited in Upper Klamath River reservoirs (GEC 2006). Downstream of Cottonwood Creek, calculations assume 10% of the total load is bedload and 24% of suspended load is sand (CDBW and SCC 2002).

Differences in lithology, topography, and dominant erosion processes can cause variations in the ratio of coarse versus fine material in the sediment supply, in the attrition rates of these materials once they reach the channel network, and in the coarse to total ratio of the sediment load. Coarse to total load ratios typically decrease in the downstream direction due to attrition and storage of coarse material and are typically most temporally and spatially variable in small basins (Benda 1994). Studies that have characterized the grain size distribution of sediment load in rivers draining the Pacific slope suggest a typical coarse (>2mm) to total load range from about 0.14 to 0.28.

4.2 Fractionation of Coarse Load Based on Bed Material Grain Size

Bed material comprises the bed and lower banks of an alluvial river, and it corresponds with the coarser fraction of the sediment load transported by the river. Bed material may transport as either bedload or intermittently as suspended load (Church 2006). Bed material is generally sampled as the subsurface material beneath any surface armor layer (Bunte and Apt 2001). Bed material is generally coarser than bedload (Parker 1990), and in systems where selective transport of finer grain size occurs, the bed material distribution can be significantly coarser than the bedload (Lisle 1995). In river systems where the equal mobility hypothesis (Parker and Klingeman 1982, Andrews 1983) is met or nearly achieved, however, the subsurface bed material distribution is typically similar to the bedload distribution. In the absence of direct field measurements of bedload, we use the grain size distribution of subsurface bed material samples as surrogates for the sizes of the coarser sediment load delivered from tributaries to the mainstem Klamath River.

Field sampling of bed material was beyond the scope of this study. Thus, we relied on existing bed material sample data from previous studies of Klamath River tributaries to characterize the coarse sediment fractions supplied to the mainstem channel. The bed material grain size distributions were sampled by different entities in different morphologic stream units (e.g., bars vs. riffles) over different time periods (ranging from 1980 to 2007). All of the data presented are from volumetric samples of bed material collected with a McNeil (McNeil and Ahnell 1964) or a similar barrel core sampler. The McNeil or barrel samplers used did not have the same diameters, which can lead to biases in the grain sizes collected. Collectively, the different data sources should be viewed independently because of potential differences associated with sample locations, diameter of sample barrel, and sampling time period. Descriptions of each bed material data source are provided below and in Table 9. The majority of the data sources provided results for several samples for tributary reaches of interest. In order to provide a characteristic distribution for each tributary, we calculated an average distribution for tributaries with multiple samples by taking the arithmetic average of the percent retained for each sieve size used in the post processing of the samples, which is equivalent to lumping all the samples together for joint sieving after taking into account different initial sample masses (Bunte and Apt 2001). Data for individual and average tributary bed material samples are presented in Appendix A.

Table 9. Summary of bed material data from Klamath River tributaries.

Tributary	River Mile[1]	Source	Sample year	Diameter of sampler (in)	Surface layer definition and treatment
Cottonwood Creek	184.9	Holmquist-Johnson and Millhous 2009	2007	22.5	Largest particle in surface layer, analyzed separately from subsurface
Shasta River	179.3	Buer 1981	1980	14	Top 10 cm (4 in) of sediment, analyzed separately from subsurface
Horse Creek	149.6	Holmquist-Johnson and Millhous 2009	2007	22.5	Largest particle in surface layer, analyzed separately from subsurface
Scott River	145.1	Sommarstrom et al. 1990	1990	6	Unknown, assumed integrated with subsurface
Trinity River	43.4	GMA 2001b	2000	24	Largest particle in surface layer, analyzed separately from subsurface
Trinity River	43.4	GMA 2010	2009	24	Largest particle in surface layer, analyzed separately from subsurface
South Fork Trinity River	43.4	GMA 2003	2003	24	Largest particle in surface layer, analyzed separately from subsurface
Blue Creek	16.1	Holmquist-Johnson and Millhous 2009	2007	22.5	Largest particle in surface layer, analyzed separately from subsurface

[1] The River Mile given is the location of the tributary confluence with the Klamath River. River miles reported here are derived from a recent high resolution streamline and may vary from those reported in the PacifiCorp sediment budget.

4.2.1 Shasta River

The California Department of Water Resources (DWR) conducted a study to determine the effects of hydrologic and watershed changes on the gravel budget and distribution of spawning gravel in the Klamath River from Iron Gate to the Humbug Creek confluence and in the Shasta River downstream of Lake Shastina (Buer 1981). As part of this gravel investigation, DWR collected surface and subsurface bulk samples from bar deposits by driving a 14-inch diameter cylinder into the deposit. The surface layer consisted of the top 10 cm (4 inch) of the bed and the subsurface layer included the next 10 cm (4 inch) of sediment or sediment at a depth of 10–20 cm (4–8 in). Sediment samples were analyzed using 12 sieve sizes ranging from 152.4 mm (6 in) to 0.075 mm (standard sieve #200). For the purposes of this study, we assumed the 0.075 mm sieve approximates the 0.063 mm split between sand and silt size fractions.

For this study, we analyzed the 10 subsurface (i.e., sediment at a 10 to 20 cm [4 to 8 inch] depth) bulk samples that DWR collected from the Shasta River. All of the bulk samples from the Shasta River were collected in the lower, steeper reaches downstream of Interstate Highway 5 and are assumed representative of the coarse sediment load delivered from the Shasta River to the Klamath River. The 10 bulk subsurface samples were averaged together to provide one characteristic distribution. The distributions of individual samples are shown in Appendix A.

4.2.2 Scott River

Sommarstrom et al. (1990) investigated the impacts of sediment production from granitic terrane in the Scott River basin, focusing on: (1) sources of granitic sediment production; (2) granitic sediment storage and transport in the Scott River; and (3) extent of impact of granitic sediment on salmon and steelhead spawning habitat in the Scott River and selected tributaries. They collected 238 McNeil samples at 11 sites in the Scott River in 1989. Sample sites were located in riffles, and generally 20 to 25 samples were collected per site. A 6-inch diameter McNeil sampler was used to collect samples to a depth of 6 inches. Details about whether the surface material was excluded from the subsurface material were not provided, and it is assumed that samples integrate both surface and subsurface material. A limited number of sieves (25, 12.5, 6.3, 4.75, 2.36, and 0.85 mm) were used to divide the bed material samples. No additional breakdown for coarse gravel and cobble are available. Sommarstrom et al. (1990) assumed that 100 mm was the maximum particle size for their samples based on their field observations, and this assumption is adopted herein.

For the purposes of this report, we focus on the bed material samples collected in Reach 1 of the Scott River by Sommarstrom et al. (1990). Reach 1 is the furthest downstream and is inferred to be the most representative of the coarse sediment load delivered to the Klamath River. Reach 1 includes study sites A and B where a total of 45 bulk samples were collected. We use the average of these bulk samples (presented in Table 3-4 of Sommarstrom et al. 1990). Bedload from Scott River to Klamath River may be finer than indicated by the bulk samples due to the possible inclusion of the surface layer.

4.2.3 Trinity River

Graham Matthews and Associates (GMA) collected bulk samples on the mainstem Trinity River between Lewiston Dam (RM 111.5) and Junction City (RM 80.3) as part of monitoring baseline gravel quality and evaluating the effectiveness of restoration actions (GMA 2001b and 2010). GMA's mainstem Trinity River monitoring focused on the section of river where much of the mainstem salmon spawning occurs and has been the most impacted by reduced flows (GMA

2001b). In 2000, GMA collected bulk samples at eight sites on the Trinity River that characterize spawning areas downstream of key tributaries. Using a 2-ft diameter McNeil sampler, two bulk samples were collected along a cross-section at each site. Samples were taken from sediment patches indicative of spawning substrate in the reach. Surface sediment, defined as the depth of the largest surface particle, was sampled and analyzed separately from the subsurface sediment. Using a combination of wet (field) sieving for the coarser fractions and dry (lab) sieving for the finer fraction, all sediment samples were processed at ½ Φ intervals from 256 to 0.063 mm.

In 2009, GMA reoccupied 7 of the 8 study sites on the mainstem Trinity River that were sampled in 2000 (GMA 2010). Where possible, sampling locations were placed along the same cross-sections as in 2000, and where earlier cross-sections could not be located or were no longer suitable, the 2009 sampling cross-sections were placed in the vicinity of the 2000 study sites. Sampling and processing methodology from 2000 were repeated in 2009, except that three bulk samples were collected at each study site rather than two. For the purposes of this report, we analyzed the composite subsurface bulk sample (i.e., the combined sample from two pits at each site) collected in 2000 at the seven sites repeated in 2009. From the 2009 sampling campaign, we looked at the composite subsurface bulk sample (i.e., the combined sample from three pits at each site) collected from each of the seven sites that were repeated from 2000. Average bulk sample results for the mainstem Trinity River are detailed in Section 5.2 and grain size distributions for individual samples are shown in Appendix A. Results from 2000 are also compared with samples from 2009. Because Trinity River samples are located more than 80 miles upstream of its confluence with the Klamath River, bedload entering the Klamath River from the Trinity River may be substantially finer than indicated by the bulk samples.

As part of a separate water quality study in 2003 funded by the California Department of Fish and Game, GMA collected bulk samples on the South Fork Trinity (GMA 2003). Sampling protocol was similar to the GMA studies described above. A total of four subsurface bulk samples were available for incorporation into this report.

4.2.4 Additional Klamath River tributaries

The United States Geological Survey (USGS) collected bed material samples in December 2007 at several locations in the Klamath River from Iron Gate Dam to Blue Creek, as well as in select Klamath River tributaries (Sutton and Millhous 2008; Holmquist-Johnson and Millhous 2009). Sediment samples were used for flushing flow analyses (Holmquist-Johnson and Millhous 2009) and for redd scour studies (Sutton and Millhous 2008). Sediment samples were broken into surface fines (sand deposited on top of the armor layer), surface armor layer, and subsurface material. Samples were collected using a 55-gallon drum driven into the bed, which typically has a diameter of 22.5 inches and results in a volumetric sample similar to a large McNeil sampler. Sediment samples were processed at ½ Φ intervals from 256 to 45 mm, and from 45 to 0.063 mm using a combination of U.S. standard sieve sizes (e.g., 1", ¾", ½" sieves) that is comparable with using ½ Φ interval sieves over this range.

For this report, we utilized subsurface bulk samples from Cottonwood, Horse, and Blue creeks. Based on Sutton and Millhous (2008), Horse Creek samples were collected at a site located about 1 mile upstream of the confluence with the Klamath River. The Blue Creek sample was excavated from a bar deposited in the mainstem Klamath River channel just downstream of the Blue Creek confluence (same side of the river as the tributary junction). The bar was coarser than other nearby sediment deposits and is inferred to be representative of the Blue Creek sediment input (R. Milhouse, pers. comm., 2010.). The Cottonwood Creek sample is also collected from within the Klamath River channel just downstream of the Cottonwood Creek confluence. Due to the close proximity of Cottonwood Creek to Iron Gate Dam, which traps all upstream coarse sediment inputs, it is inferred that the Cottonwood Creek sample is either material from the tributary or from bank erosion within the short reach of Klamath River channel between Cottonwood Creek and the dam.

5 ESTIMATED SEDIMENT DELIVERY TO THE KLAMATH RIVER

Existing information on sediment delivery and grain size distribution discussed in Section 3 and Section 4 above provide the basis for extrapolating sediment delivery in source areas where information is missing or incomplete (Section 5.1) and estimating cumulative average annual delivery of coarse and fine sediment to the Klamath River between Keno Dam and the Pacific Ocean (Section 5.2).

5.1 Extrapolation of Sediment Delivery in Sources Areas Where Information is Missing or Incomplete

Existing information about sediment delivery is missing or incomplete for several source areas encompassing 1,330 mi^2 (20 %) of the Lower Klamath basin downstream of Iron Gate Dam:

- Iron Gate Dam to Cottonwood Creek, including portions of the Willow Creek and Bogas Creek watersheds outside Klamath National Forest lands;
- Cottonwood Creek to Shasta River;
- Portions of the Shasta sub-basin outside Klamath National Forest lands;
- The three largest tributary watersheds in the Lower-Middle Klamath sub-basin: Camp Creek, Red Cap Creek, and Bluff Creek; and
- The Lower Klamath sub-basin.

Sediment delivery from these source areas was extrapolated using existing sediment delivery rates reported for similar terrain types in nearby watersheds.

5.1.1 Iron Gate Dam to Cottonwood Creek

Iron Gate Dam to Cottonwood Creek has a local source area of 150.6 mi^2 (2.2% of the Lower Klamath basin downstream of Iron Gate Dam). The Klamath National Forest estimated sediment delivery from 51.6 mi^2 (34.2%) of the area as part of the 2004 CWE analysis. This area is underlain by older volcanics, with 7.4% of the area having hillslope gradients steeper than 35%. The remaining portion of the watershed lacking sediment delivery information (99.1 mi^2 [65.8%]) is predominately underlain by older volcanics (80%), with 10.3% of the area having hillslope gradients steeper than 35%. Because the two areas have very similar terrain types, the average annual sediment delivery rate (66 tons mi^{-2} yr^{-1}) from the portion of the area included in the 2004 CWE analysis was used to extrapolate sediment delivery from the remaining area. Total estimated sediment delivery from the Iron Gate Dam to Cotton Creek area is 9,961 tons yr^{-1}.

5.1.2 Cottonwood Creek to Shasta River

Cottonwood Creek to Shasta River has a total source area of 17.8 mi^2 (<0.3% of the Lower Klamath basin downstream of Iron Gate Dam). The small area is underlain predominantly by hard metamorphic rocks (69% of area) as well as sedimentary rocks (26%) and older volcanics

(4%). Approximately 47% of the area has hillslope gradients steeper than 35%. The lower Shasta River sub-basin is analogous in that it is underlain predominantly by hard metamorphic rocks (97% of area), and approximately 44% of the area has hillslope gradients steeper than 35%. The 2004 CWE analysis reported an average sediment delivery of 121 tons mi^{-2} yr^{-1} in the Little Shasta sub-basin. Because the two areas have similar terrain types, the average annual sediment delivery rate from the Little Shasta River sub-basin was used to extrapolate sediment delivery from Cottonwood Creek to Shasta River. Total estimated sediment delivery from the Cottonwood Creek to Shasta River source area is 2,155 tons yr^{-1}.

5.1.3 Shasta River

The Shasta River sub-basin (786 mi^2, 11.7% of basin area downstream of Iron Gate Dam) is significantly larger than any other tributary in the 13.4 mile reach of the Klamath River between Iron Gate Dam and the Shasta River confluence. The 2004 CWE analysis divided Klamath National Forest lands in the Shasta basin (244 mi^2 [31% of the Shasta basin]) into three subwatershed areas: Little Shasta (81.5 mi^2), Lower Shasta (61.8 mi^2), and Whitney-Sheep Rock (100.5 mi^2). The 2004 CWE analysis estimated an annual sediment delivery rate of 60 tons mi^{-2} yr^{-1} for Little Shasta, 121 tons mi^{-2} yr^{-1} for Lower Shasta, and 22 tons mi^{-2} yr^{-1} for Whitney-Sheep Rock. The low rates in Little Shasta and Whitney-Sheep Rock are the result of being underlain predominantly by High Cascades volcanic rocks (99% and 79%, respectively) and having 10% or less of the area with hillslope gradients steeper than 35%. The higher rates in Lower Shasta are the result of being underlain by hard metamorphic rocks (97%) and having 43% of the area with hillslope gradients steeper than 35%. Sediment delivery in the Whitney-Sheep Rock area is disconnected from the Klamath River by closed drainage patterns (e.g., closed basins without well-defined outlet channels).

Approximately 542 mi^2 (69%) of the Shasta basin occurs outside of Klamath National Forest Lands and lacks sediment delivery information. Approximately 126 mi^2 of this area (16% of Shasta basin) is disconnected from delivering sediment to the Klamath River by either natural closed drainage patterns or by Dwinnell Reservoir. The remaining (connected) area not included in the CWE analysis (416 mi^2 [53% of the Shasta basin]) is predominantly underlain by hard metamorphic rocks (108 mi^2 [29%]), older volcanics (99.8 mi^2, [26.8%]), and unconsolidated surficial deposits (143 mi^2 [38.5%]). Approximately 19% of the area has hillslope gradients steeper than 35%. Sediment delivery rates reported in the 2004 CWE analysis for areas with similar geology and slope were used to extrapolate sediment delivery from the connected source area in the Shasta basin not included in the CWE analysis (Appendix B Table 1). Estimated sediment delivery from these areas is 9,128 tons yr^{-1}, and total estimated sediment delivery from the Shasta sub-basin is 21,544 tons yr^{-1}.

5.1.4 Lower-Middle Klamath sub-basin

Six Rivers National Forest estimated sediment delivery from the Lower-Middle Klamath sub-basin area as part of the Lower Middle Klamath Watershed Analysis (refer to Section 3.3.2 above) (USDA Forest Service 2003). The watershed analysis area is underlain by predominantly hard metamorphic rocks (91% of area) of the Galice Formation, Rogue Formation, and Western Hayfork Terrane. Serpentinitic volcanic rocks and some metasedimentary rocks within the Galice Formation are prone to deep-seated landsliding. The remaining watershed analysis area is underlain by igneous intrusive rocks (3.4%) and soft metasedimentary rocks of the Picket Peak Terrane (5.6%).

The watershed analysis excluded the three largest tributary watersheds in the Lower-Middle Klamath sub-basin: Camp Creek (42.0 mi^2), Red Cap Creek (63.1 mi^2), and Bluff Creek (74.1 mi^2) (totaling 2.7% of the Lower Klamath basin downstream of Iron Gate Dam). Lacking sediment delivery information for these tributary watersheds, sediment delivery was extrapolated using the average annual unit-area sediment delivery rates for specific bedrock geologic units reported in the Lower-Middle Klamath Watershed Analysis area (Table 8, Appendix B Table 2). Camp Creek and Red Cap Creek are underlain predominantly by hard metamorphic and igneous intrusive rocks similar to those found in the Lower-Middle Klamath Watershed Analysis area. A significant portion of the Bluff Creek watershed area (32% of the area), however, is underlain by soft metasedimentary rocks of the Picket Peak Terrane that are prone to deep-seated landsliding and earthflow. Extrapolation of sediment delivery from Picket Peak Terrane in the Bluff Creek watershed is based on sediment delivery rates reported for similar terrane in the Trinity River and South Fork Trinity sediment TMDLs (Appendix B Table 2). Estimated sediment delivery from the three large tributaries is as follows: 45,754 tons yr^{-1} from Camp Creek, 42,775 tons yr^{-1} from Red Cap Creek, and 100,668 tons yr^{-1} from Bluff Creek (Appendix B Table 2).

5.1.5 Lower Klamath sub-basin

The lower Klamath sub-basin encompasses 367 mi^2 (5.5% of basin area downstream of Iron Gate Dam) from the Trinity River confluence near Weitchpec to the mouth of the Klamath River at the Pacific Ocean. A number of small tributaries drain to the Klamath River in this reach, the largest of which is Blue Creek (125 mi^2). The area is partially covered by three different sources of geospatial data: USDA Forest Service Region 5 bedrock mapping covers 77% of area, USGS geodata (Ludington et al. 2006) covers 8% of the area, and CGS geodata for portions of the Requa and Childs Hill Quads covers 15% of the area. Map unit nomenclature for the various sources of geologic information is inconsistent. The majority of the area (68%) is underlain by metasedimentary rocks of the Broken Formation and metavolcanic rocks and schist of the Pickett Peak Formation, both of which are part of the Eastern Belt Franciscan Complex in the Coast Range geomorphic province. Galice metasediments and ophiolitic rocks of the Western Klamath Terrane underlie 17% of the area, and the Rattlesnake Creek subterrane within the Western Paleozoic and Triassic Terrane underlies about 7% of the area.

The Hunter Creek watershed is in the Coast Range Geomorphic Province and is underlain predominantly by the Eastern Belt Franciscan Complex, the dominant geologic unit in the Lower Klamath sub-basin. Inventories of sediment delivery in Hunter Creek resulted in a unit area sediment delivery rate of 773 t mi^{-2} yr^{-1} (Simpson Resource Company 2002) that is used herein to extrapolate sediment delivery to other similar areas of the Lower Klamath sub-basin where no other sources of sediment delivery information have been identified. Sediment delivery from portions of the Lower Klamath sub-basin underlain by soft metasedimentary rocks of the Picket Peak Terrane and mélange of the Eastern Belt Franciscan complex that are prone to deep-seated landsliding and earthflow were extrapolated based on sediment delivery rates reported for similar terrane in the Trinity River and South Fork Trinity sediment TMDLs. Estimated sediment delivery from the Lower Klamath sub-basin is 480,927 tons yr^{-1}.

5.2 Average Annual Sediment Delivery to the Klamath River

Existing information on sediment delivery to the Klamath basin (described in Section 4) was combined with extrapolated estimates of sediment delivery from source areas lacking information (described in Section 5.1) to derive cumulative average annual sediment delivery to the Klamath River from Keno Dam (RM 192.7) to the Pacific Ocean (RM 0.0)(Table 10). Estimates of cumulative sediment delivery to the Klamath River do not account for transfer of sediment to and from storage in tributary or mainstem channels nor attrition by abrasion. Cumulative coarse sediment delivery will be less than presented in Table 10 when storage and attrition are considered.

Table 10. Estimated sediment delivery to the Klamath River from Keno Dam to the Pacific Ocean.

Source area	RM[9]	Source area (mi^2)	Cumulative delivery[10] (tons y^{-1})		
			Total	≥0.063 mm	<0.063 mm
Keno Dam To Iron Gate Dam[1]	192.7	660	151,000	24,160	126,840
Iron Gate Dam to Cottonwood Creek[2]	184.9	151	160,961	25,754	135,207
Cottonwood Creek[3]	184.9	99	175,560	30,426	145,135
Cottonwood Creek to Shasta River[2]	179.3	18	177,715	31,115	146,600
Shasta River[2]	179.3	516	199,259	38,009	161,250
Shasta River to Beaver Creek[3]	163.3	106	231,710	48,393	183,316
Beaver Creek[4]	163.3	109	279,869	63,804	216,065
Beaver Creek to Scott River[3]	145.1	154	373,073	93,630	279,443
Scott River[5]	145.1	814	980,393	287,972	692,421
Scott River to Grider Creek[3]	129.4	128	1,048,860	309,881	738,978
Grider Creek to Indian Creek[3]	108.4	105	1,099,934	326,225	773,709
Indian Creek[3]	108.4	135	1,173,246	349,685	823,561
Elk Creek[3]	107.1	95	1,211,930	362,064	849,866
Clear Creek[3]	100.1	111	1,253,972	375,517	878,454
Dillon Creek[3]	85.8	73	1,282,389	384,611	897,778
Indian Creek to Dillon Creek[3]	85.8	137	1,354,759	407,769	946,990
Dillon Creek to Salmon River[3]	66.5	109	1,440,282	435,137	1,005,146
Salmon River[3]	66.5	751	1,760,904	537,736	1,223,169
Salmon River to Camp Creek[7]	57.3	27	1,785,769	545,693	1,240,077
Camp Creek[6]	57.3	42	1,831,523	560,334	1,271,190
Camp Creek to Red Cap Creek[7]	53.0	26	1,855,021	567,853	1,287,168
Red Cap Creek[6]	53.0	63	1,897,796	581,541	1,316,255
Red Cap Creek to Bluff Creek[7]	49.8	18	1,913,925	586,702	1,327,223
Bluff Creek[6]	49.8	74	2,014,594	618,916	1,395,678
Bluff Creek to Trinity River[7]	43.4	23	2,035,830	625,712	1,410,118
Trinity River[5]	43.4	2,274	5,353,164	1,687,259	3,665,905
Blue Creek[8]	16.1	125	5,455,971	1,720,157	3,735,814
Trinity River to Mouth[8]	0.0	367	5,834,091	1,841,155	3,992,936

[1] Source: Reservoir sediment volumes reported in GEC 2006, sedimentation rates reported in Stillwater Sciences 2008.

[2] Source: CWE analysis for Klamath National Forest lands (UDSA Forest Service 2004). Delivery from remaining areas extrapolated based on CWE modeled sediment delivery rates in similar terrain. Excludes source areas upstream of Dwinnell Reservoir and other disconnected areas in Shasta Valley.

[3] Source: CWE analysis for Klamath National Forest lands (UDSA Forest Service 2004).

[4] Source: CWE analysis for Mt. Ashland Late-Successional Reserve Habitat Restoration and Fuels Reduction Project (Elder 2006).

[5] Source: Sediment TMDLs (NCRWQCB 2005; EPA 1998, 2001). Excludes source areas upstream of Trinity Dam.

[6] Delivery from Camp, Red Cap, and Bluff creeks extrapolated using unit-area delivery rates by geologic unit reported in the Lower Middle Klamath Watershed Analysis.

[7] Source: Lower Middle Klamath Watershed Analysis (USDA Forest Service 2003).

[8] Source: Extrapolated from sediment delivery rates for similar terrain in Hunter Creek reported in the Green Diamond Habitat Conservation Plan (Simpson Resource Company 2002) and in the South Fork Trinity River sediment TMDL (EPA 1998).

[9] River miles reported here are derived from a recent high resolution streamline and may vary from those reported in the PacifiCorp sediment budget.

[10] Density = 1.5 tons yd^{-3}. Mass reported in US short tons. Above Cottonwood Creek, assumes 16% of total load is ≥0.063 based on grains size distribution of reservoir sediment (GEC 2006). Below Cottonwood Creek, assumes 10% of total load is bedload and 24% of suspended load is sand ≥0.063 (CDBW and SCC 2002). Coarse sediment delivery to the Ocean is less than presented in this table when attrition by abrasion is considered.

The upper Klamath basin encompassing the Modoc Plateau and High Cascades terranes generally has low sediment delivery rates related to resistant rock, low gradient topography, and hydrologic disconnection. These terrane types result in relatively little sediment delivery (199,300 tons yr^{-1} or 3.4% of the total basin delivery downstream of Keno Dam) to the 13.4 mi reach of the Klamath River from Keno Dam to the Shasta River.

The three tributaries that contribute the largest amount of sediment to the lower Klamath River are the Scott River (814 mi^2 source area), Salmon River, (751 mi^2 source area) and Trinity River (2,274 mi^2 source area). The Scott River supplies 607,300 tons (10.4% of the total basin delivery downstream of Keno Dam), more than doubling supply to the Klamath River at its confluence. The Salmon River supplies 320,600 tons (5.5% of the total basin delivery downstream of Keno Dam), increasing supply to the Klamath River by 22% at its confluence. Tributaries in the Lower-Middle Klamath sub-basin between Salmon River and Trinity River collectively increase sediment delivery by 4.7%. The Trinity River supplies 3,317,300 tons (56.9% of the total delivery delivery downstream of Keno Dam), more than doubling supply to the Klamath River at its confluence.

The California Department of Boating and Waterways and the California State Coastal Conservancy characterized coarse sediment (>0.062 mm) flux from California's coastal rivers and the potential effects of dams at reducing coarse sediment supply to beaches (CDBW and SCC 2002, Willis and Griggs 2003). Suspended sediment load and bedload were estimated for the Klamath River near Klamath using a standard rating curve technique in which measurements of bedload and suspended sediment load were correlated with water discharge. Daily measured and estimated suspended sediment fluxes were summed by year for water years 1911-1926, 1956-1996, and 1998-1999. An average value for the percent of suspended sediment coarser than 0.062 mm was calculated from suspended sediment grain size distributions and used to reduce the annual total suspended sediment flux to the amount of sand-sized sediment discharge. Bedload rating curves were based on limited bedload sampling data. Grain size data from the channel bed were used to assess the sand and gravel fraction of the bed load. Annual sand and gravel load were summed to determine the mean annual flux (>0.062) over the period of record. Estimated average annual sediment flux (>0.062 mm) from the Klamath River near Klamath (with all dams in in place) was 2,502,200 tons yr^{-1} (CDBW and SCC 2002, Willis and Griggs 2003). Maximum uncertainty in the annual suspended sediment discharge estimate was ± 37%. The estimated cumulative average annual sediment delivery from the Klamath basin downstream of Keno Dam (this study) and the estimated sediment flux from the Klamath River to the Pacific Ocean (Willis and Griggs 2003) agree within 30% (Table 11).

Table 11. Comparison of cumulative basin sediment delivery (≥0.063 mm) downstream of Keno Dam and sediment flux (≥0.063 mm) from the Klamath River to the Pacific Ocean.

Estimate[1]	Tons y^{-1}	Method	Period
Cumulative annual basin sediment delivery downstream of Keno Dam	1,841,200	Modeled and/or empirically derived sediment delivery rates	Varies (generally post-1920s)
Total annual sediment flux from the Klamath River to the Pacific Ocean	2,502,200	Sediment rating curves	1911-1926, 1955-1996, 1998-1999
Difference	661,000 (30%)		

[1] Estimates exclude sediment delivery upstream of Keno Dam on the Klamath River, Dwinnell Dam on the Shasta River, and Lewiston Dam on the Trinity River.

5.3 Klamath Tributary Bed Material Grain Size Distributions

The averaged tributary bed material grain size distributions indicate relatively similar distributions for all the tributaries where bulk sample data were available (Figure 5). The size distribution of samples collected in the mainstem Trinity River in 2009 depart from the general trend. No distinct differences in grain size trends are apparent based on tributary distance downstream of Iron Gate Dam or tributary drainage area. The lack of major differences in the grain size distributions of tributary bed material may be attributable to the bedrock geology in the Lower Klamath basin, which is predominantly a mixture of metamorphic and igneous intrusive units that tend to be distributed in similar proportions within different sub-watersheds (Figure 3). In addition, the similar climate and geology likely leads to similar flow regimes on a unit-area basis that result in comparable sediment transport capacities relative to drainage basin size and sediment supply and may further promote bed material similarity.

The averaged tributary bed material size distributions have similar geometric means, ranging from 10 to 22 mm (Table 12, Figure 5), which are classified as medium to coarse gravel using the Wentworth scale. The average tributary D_{84} (particle that which 84% is finer than) range from very coarse gravel to small cobble, and the D_{16} range from very coarse sand to fine gravel. The averaged Klamath tributary bed material distributions all indicate a relatively small fraction of sand (2–0.063 mm), ranging from about 10 to 21% (Figures 5 and 6). The majority (60–83%) of the bulk samples are comprised of gravel (2–64 mm), while the fraction of cobbles (> 64 mm) ranges from about 3–20% (Figure 5). Individual bed material samples from a given reach illustrate significant spatial variation in subsurface composition as well as substantial deviation from the averaged tributary distributions (Appendix A). In the Shasta River, for example, the sand content ranges up to 42 % and the cobble fraction up to 30% for individual samples, compared to the average sand fraction of 18% and cobble fraction of 9%.

Table 12. Summary of bed material data statistics for Klamath River tributaries.

Tributary	Geometric mean (mm)	% Fines (< 2 mm)	% Gravel (2-64 mm)	% Cobble (> 64 mm)
Cottonwood Creek	10.6	21%	65%	13%
Shasta River	11.1	17%	74%	9%
Horse Creek	13.5	15%	64%	21%
Scott River	10.0	20%	80%[1]	NA
Trinity River (2000)	12.8	18%	62%	20%
Trinity River (2009)	21.7	9%	57%	33%
South Fork Trinity River	12.6	10%	75%	20%
Blue Creek	10.5	13%	84%	3%

[1] The largest sieve size used in processing bulk samples on the Scott River was 25 mm, and thus all material larger than 2 mm is included as gravel.

As discussed earlier, bedload will generally be finer than bed material (e.g., Parker 1990). Differences between the bedload size distribution and the bed material size distribution are spatially and temporally variable depending on several factors, including the ratio of sediment supply to transport capacity and the duration and magnitude of sediment transporting flow events (Lisle 1995). Lisle (1995) compared the ratio of bedload to bed material size distributions from 13 gravel bedded rivers from around the world, and found that bedload was increasingly finer relative to bed material toward more proximal channel locations (i.e., channels with smaller drainage areas closer to the dominant sediment sources). Lisle (1995) found that the ratio of bed material size to bedload size decreased with increasing drainage area, bank-full discharge, and dimensionless stream power. The distal location of the sample sites (presented herein) within large tributary drainage areas (i.e., samples are typically from reaches close to the Klamath confluence) strongly suggests that differences between bed material size distribution and bedload size distribution delivered to the Klamath River are small. However, the fraction of sand sized material delivered to the Klamath River is under represented in the bed material samples because a significant proportion of sand-sized material transports as suspended load. Without either direct bedload measurements or data to numerically model the transport capacity and bedload distribution, the differences between bedload delivered to the Klamath River and tributary bed material samples presented herein cannot be quantified.

Subsurface bulk samples from the mainstem Trinity River show a consistent coarsening from 2000 to 2009 (Appendix A Figure 3) (GMA 2010). The coarsening is apparent throughout the majority of the distribution (128 to 0.5 mm) except at the extreme tails, which account for a small percentage of the sample. With each individual study site coarsening, the averaged distributions follow suit with the sand fraction decreasing from 18 to 10%, the gravel fraction decreasing from 62 to 57%, and the cobble fraction increasing from 20 to 33%. Note that the majority of the cobble increase occurs in the small cobble range of 64–90 mm. GMA (2010) hypothesized that the coarsening may be attributable to the restoration of a more natural hydrograph downstream of Lewiston Dam with increased frequency of sediment transport and capacity for flushing finer sediment from the bed. An additional explanation may be attributable to the extensive spawning gravel augmentation that has occurred downstream of Lewiston Dam that is likely voluminous enough to alter the bed material distribution through the reach from Lewiston Dam to Junction City. Although gravel augmentation may affect the bed material distributions in this reach, it is unlikely to alter the size of the load delivered by the Trinity River to the Klamath River because the amount of augmented gravel is only a small fraction of the natural sediment load from the Trinity River basin. Restoring the hydrograph to a more natural state below Lewiston Dam, however, does have the potential to alter the size and quantity of sediment delivered from the Trinity River.

6 PREDICTED SEDIMENT RELEASE FROM DAM REMOVAL AS A PROPORTION OF AVERAGE ANNUAL BASIN SEDIMENT DELIVERY

Numerical modeling predicted a range of coarse (≥ 0.063 mm) and fine (<0.063 mm) sediment loads that may be released by dam removal by testing different hydrologic scenarios during drawdown and dam removal and by varying the assumed new equilibrium channel dimensions within the former reservoir impoundments (Table 13)(Stillwater Sciences 2008). The modeling predicted that 18–40% of the total volume of sediment stored in reservoir impoundments would be eroded following dam removal, delivering an estimated 1.4 to 3.2 million tons of sediment to reaches downstream of Iron Gate Dam. About 19% of the estimated volume of eroded sediment would be coarse material (sand or coarser). Modeling also predicted that the vast majority of the sediment would be released from the reservoirs in the first year following dam removal, and thus the predicted sediment releases (Table 13) are directly compared with the cumulative average annual sediment delivery to the Klamath River downstream of Iron Gate Dam (detailed in Section 5).

Table 13. Summary of numerically modeled sediment release from Copco 1 and Iron Gate reservoirs following dam removal (Stillwater Sciences 2008).

Scenario	Volume of sediment eroded from Copco 1 and Iron Gate reservoirs (tons)		
	high	median	low
Sand and coarser (≥0.063 mm)	628,000	474,000	276,000
Silt and finer (<0.063 mm)	2,590,000	1,962,000	1,157,000
Total	3,219,000	2,436,000	1,433,000
Fraction of total reservoir deposit	40%	30%	18%
Change relative to median	32%	n/a	-41%

The modeled sediment releases from dam removal are plotted against cumulative estimated annual basin sediment delivery by River Mile in Figure 7. Comparing the ratio of reservoir sediment release to average annual drainage basin sediment delivery at specific points along the Klamath River provides an additional means of contextualizing the magnitude of likely sediment release following dam removal (Figure 8). Several key assumptions are necessary in making these comparisons:

1. The entire quantity of sediment released by erosion of reservoir deposits routes through the the Lower Klamath River to the estuary, although this will likely not be the case due to transfer of some sediment into channel storage;
2. The entire quantity of sediment delivered to the Klamath River from each sub-basin accumulates with distance downstream routes in its entirety to the estuary each year, which also does not account for the likelihood that some amount of this supply will transfer to and from channel storage;
3. Attrition of coarse material into fine material through abrasion during transport is not accounted for in the reservoir sediment release or the drainage basin sediment supply.

Although these assumptions substantially over-simplify sediment supply and transport dynamics, Figure 7 and Figure 8 provide a first-order approximation of what the sediment release from dam removal represents to the fluvial system relative to average annual background sediment delivery.

Predicted median values of fine and total sediment load released by dam removal are significantly more (by a factor of 6 or more) than the cumulative average annual fine and total sediment delivery from the drainage basin between Iron Gate Dam and the Scott River (RM 145.1). Supply from the Scott River reduces the ratio of sediment release to basin sediment delivery to 2.3 (2.6 for fine load, 1.5 for coarse load). The ratio declines to 1.3 (1.5 for fine load, 0.80 for coarse load) at the Salmon River confluence (RM 66.5) and to 0.41 (0.49 for fine load, 0.25 for coarse load) at the Trinity River confluence (RM 43.4). Predicted low values of sediment load released by dam removal are less than average annual basin sediment delivery at the Dillon Creek confluence (RM 85.5) for total load and the Salmon River confluence for fine load. Even the predicted high values of fine and total load released by dam removal are less than half the average annual fine and total load delivery from the basin at the Trinity River confluence. It is important to keep in mind that these comparisons are based on the estimated long-term average annual sediment supply from contributing drainage areas.

The sediment load supplied from the watershed in any given year will vary from the long-term annual average load based on annual hydrologic conditions, land-use practices (e.g., logging and road development or decommissioning), and other environmental factors (e.g., mass wasting and wildfire) that control sediment supply and transport. Quantifying the potential annual variations around the estimated average annual sediment supply in the entire Klamath River basin is difficult without long-term data sets describing suspended or total sediment load. However, analyzing historical sediment discharge data from nearby locations provides a reasonable indication of the potential variation and trends in annual sediment supply. Janda and Nolan (1979) summarize sediment discharge data from a variety of USGS gaging stations in Northern California, including the Klamath River watershed. The highest annual sediment yield in the Klamath River at Orleans (WY 1968–1977) was three times greater than the period average. The highest annual sediment yield in the Trinity River at Hoopa (WY 1957–1977) was a factor of 7 greater than the period average and a factor of 14 greater than the estimated long-term annual average (Janda and Nolan 1979). The period of record for the Trinity River at Hoopa includes the large flood of 1964, whereas the period of record for the Klamath River at Orleans does not. Using these observed variations in annual sediment discharge as indicators for the expected range of potential variation in annual background sediment loads, the predicted sediment release from removal of dams on the Klamath River is within the typical range of background conditions at Scott River during years with average sediment delivery and as far upstream as Beaver Creek during years with high sediment delivery.

Additional insight is gained by comparing the average annual basin sediment delivery and the anticipated annual sediment load from dam removal with daily suspended sediment loads observed during large floods. The *daily* suspended sediment load measured in the Klamath River at Orleans exceeded the estimated cumulative average *annual* basin sediment delivery at the Salmon River confluence (sediment delivery node nearest Orleans) for 5 days during the period from WY 1968 to WY 1979. The highest daily suspended sediment load in the Klamath River at Orleans during the January 1974 flood (second largest during the 81 year period of record) was greater than the median estimate of total annual sediment load released by dam removal. Suspended sediment data is not available for the Orleans gage during December 1964, the largest flood on record. Suspended sediment flux in the Trinity River at Hoopa from December 22 to 26, 1964 was approximately 25,400,000 tons, nearly 8 times the high estimate of total annual sediment release from dam removal. During 3 of the days during the 1964 flood, the daily suspended sediment flux exceeded the high estimate of total annual sediment release from dam removal. Observations from these gaging records indicate that the predicted amount of sediment released by removal of dams on the Klamath River could be considered equal or less than the background sediment flux over a single day at the Salmon River confluence during large flood events (e.g., the January 1974 flood).

7 KEY UNCERTAINTIES AND DATA GAPS

In the absence of data characterizing the quantity and size distribution of the sediment load at key locations in the Klamath River and its tributaries, existing estimates of total average annual sediment delivery rate provide the best available means of placing the anticipated sediment release from dam removal into the context of background conditions. However, the approach is based on extrapolation of unit-area sediment delivery rates derived from different methods applied to different periods of record, the rates are averaged over long spatial and temporal scales, and they lack information about the composition of the sediment supply. This approach does not provide a means of assessing the variability in delivery of different grain size fractions (fine to coarse) over different time periods (individual flood events to years) and water year types (wet to dry). Although transport capacities in the Klamath River and its tributaries are typically high relative to sediment supply, comparisons between sediment release from dam removal and basin sediment delivery become more uncertain when and where supply exceeds transport capacity, in which case significant portions of the sediment supply may transfer to storage. In addition, tributary bed material samples used in this report to characterize the grain size distribution of the coarse sediment supply from tributaries were collected over various time periods in different channel reach types and morphological positions using different methodologies. Data is lacking in many important tributaries (e.g., Beaver Creek and Salmon River).

Bedload and suspended sediment sampling over a range of flows, time periods, and sites sufficient to characterize sediment load in important sediment-producing tributaries and key reaches of the Klamath River (e.g., Iron Gate Dam to the Salmon River confluence) would provide a more direct means of relating sediment release from dam removal to background conditions. However, an intensive, long-term sediment monitoring program that includes all of these components is likely unfeasible within the time frame that the information is needed. A potentially feasible alternative approach would be to strategically collect information on bed material composition, channel geometry, and water surface slopes at study sites in key tributaries and the mainstem Klamath River. These data could be used in conjunction with historical discharge records (gaged and synthesized) to model event-based, annual (e.g., water year type), and long-term averaged sand and gravel transport rates and the grain size distribution of the coarse load in reaches of interest. Characterization of sediment storage in low gradient reaches of tributaries and the mainstem river where supply may exceed transport capacity would help to better understand the potential for and relative importance of any transfer of supply to storage. Key tributaries include those that supply the largest amount of sediment to the Lower Klamath River (Scott, Salmon, and Trinity), as well as smaller tributaries that supply sediment to the reach between Iron Gate Dam and the Salmon River confluence (e.g., Cottonwood Creek, Shasta River, Beaver Creek, Horse Creek, Grider Creek, Thompson Creek, Indian Creek, Elk Creek, Clear Creek, and Dillon Creek) where the potential effects of sediment release from dam removal are expected to be most pronounced.

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Figures

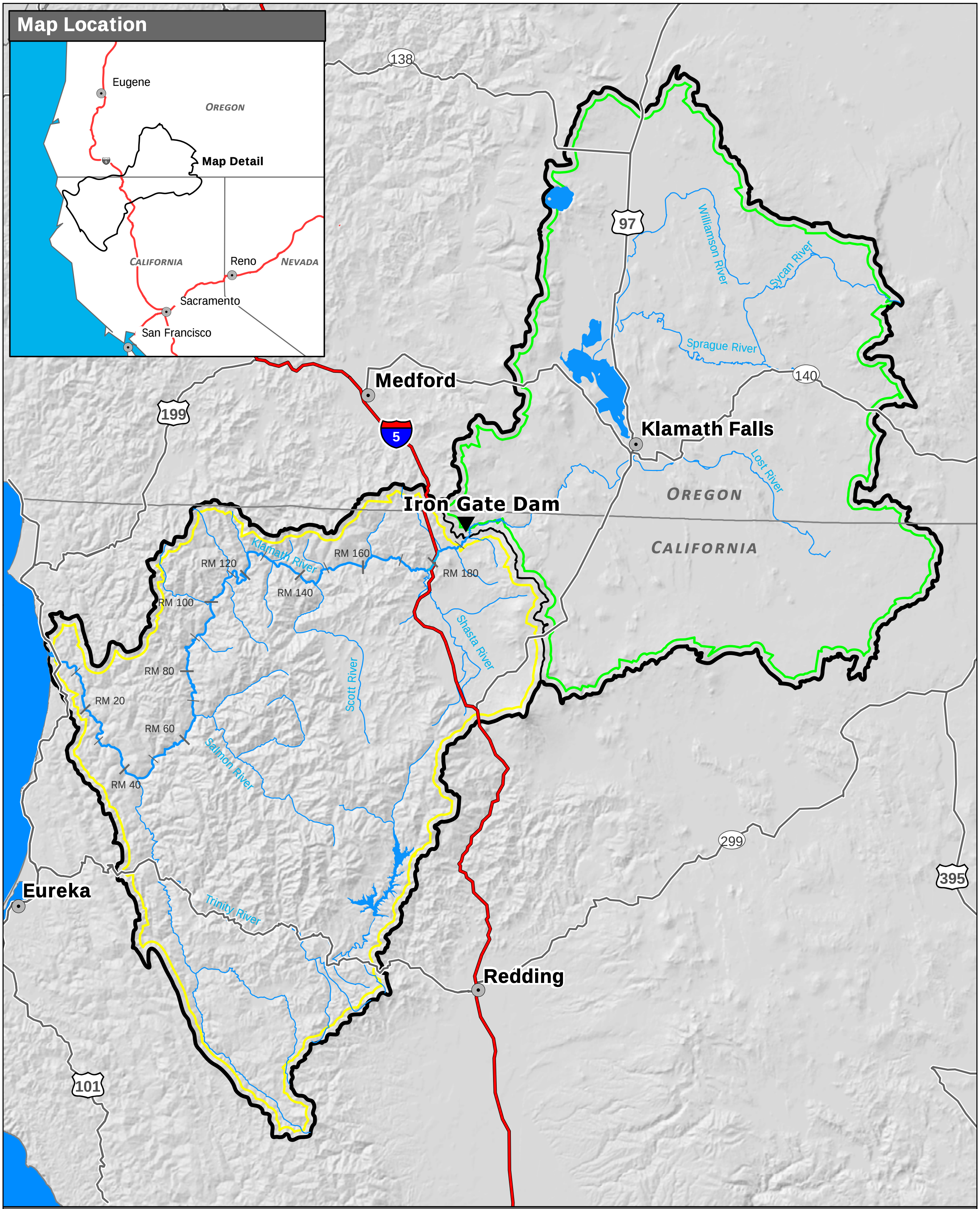
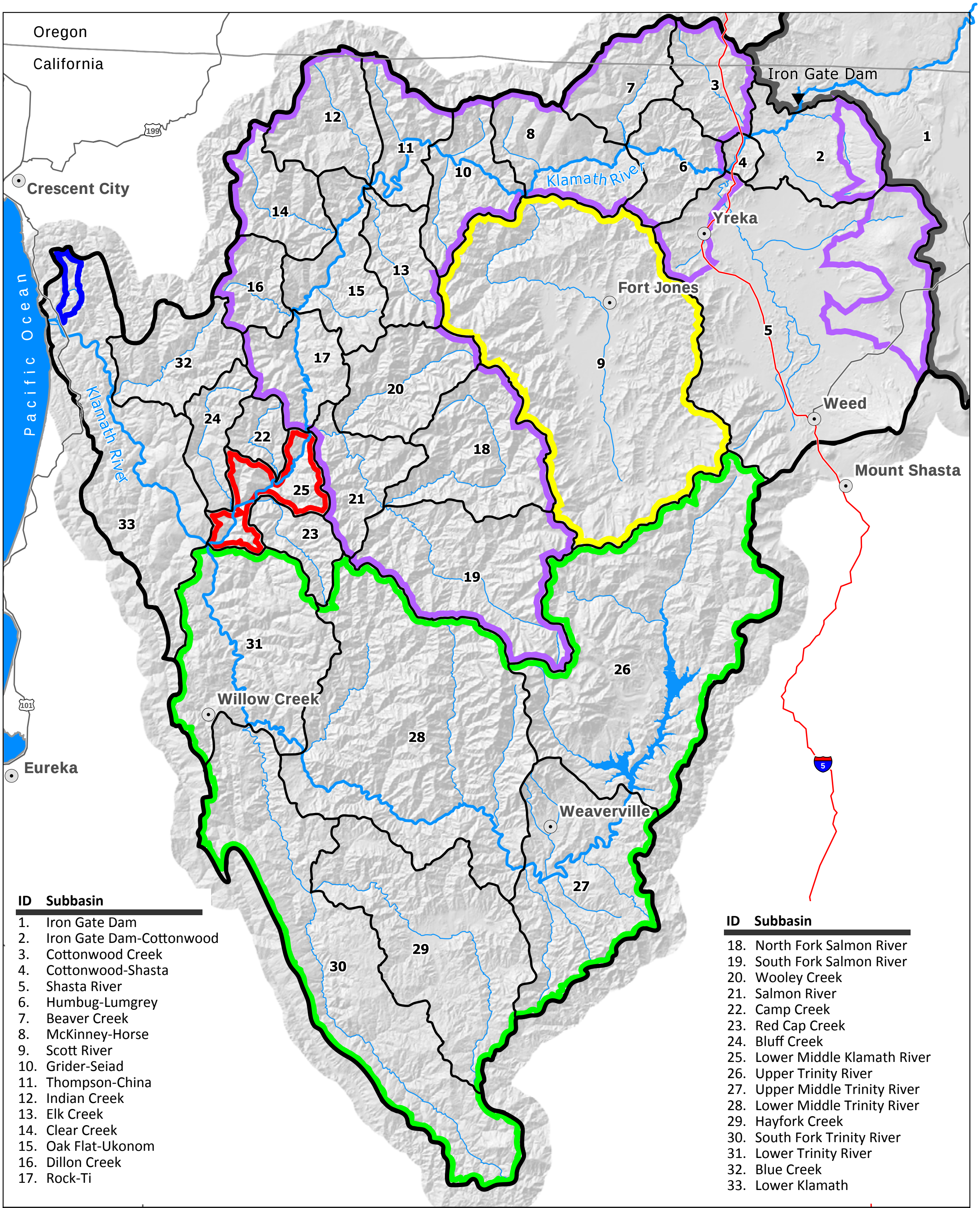


FIGURE 1 General Klamath Basin Map



ID	Subbasin
1.	Iron Gate Dam
2.	Iron Gate Dam-Cottonwood
3.	Cottonwood Creek
4.	Cottonwood-Shasta
5.	Shasta River
6.	Humbug-Lumgrey
7.	Beaver Creek
8.	McKinney-Horse
9.	Scott River
10.	Grider-Seiad
11.	Thompson-China
12.	Indian Creek
13.	Elk Creek
14.	Clear Creek
15.	Oak Flat-Ukonom
16.	Dillon Creek
17.	Rock-Ti

ID	Subbasin
18.	North Fork Salmon River
19.	South Fork Salmon River
20.	Wooley Creek
21.	Salmon River
22.	Camp Creek
23.	Red Cap Creek
24.	Bluff Creek
25.	Lower Middle Klamath River
26.	Upper Trinity River
27.	Upper Middle Trinity River
28.	Lower Middle Trinity River
29.	Hayfork Creek
30.	South Fork Trinity River
31.	Lower Trinity River
32.	Blue Creek
33.	Lower Klamath

FIGURE 2 **Lower Klamath Subbasins & Sources of Sediment Delivery Information**

Sources of Sediment Delivery Information

- Green Diamond Resource Company (2002)
- PacifcCorp Sediment Budget (2004, 2005)
- Trinity River TMDL (1998, 2001)
- Six Rivers National Forest Lower Middle Klamath Watershed Analysis (2003)
- Klamath National Forest Cumulative Watershed Effects Analysis (2004)
- Scott River TMDL (2009)

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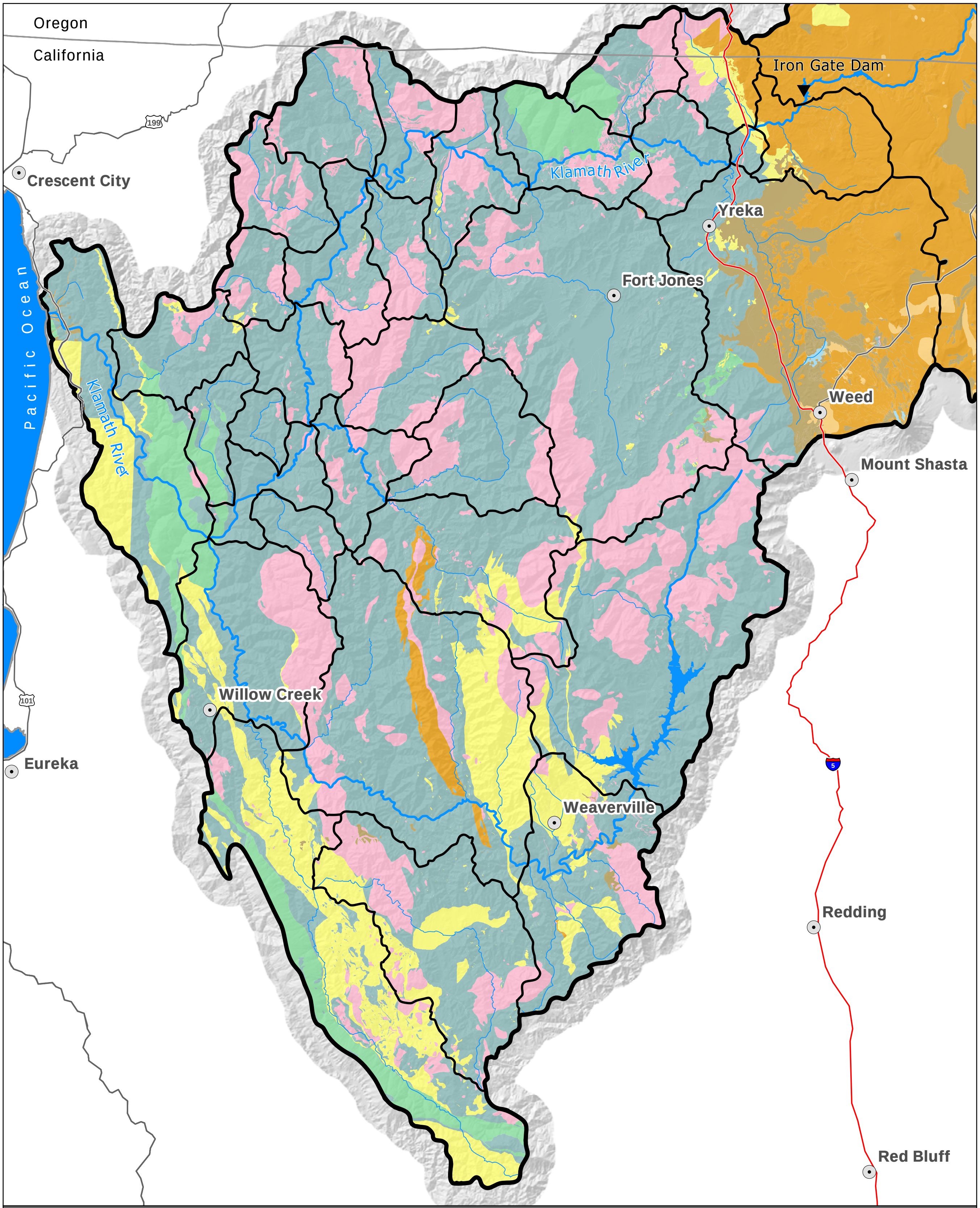


FIGURE 3 **Lower Klamath Basin Geology**

Geology

🟦	ice, water	🟧	Older volcanic
🟪	Igneous Intrusive	🟨	Younger volcanic
🟩	Metamorphic Hard	🟫	Unconsolidated
🟨	Sedimentary	🟩	Metasediment soft

Stillwater Sciences

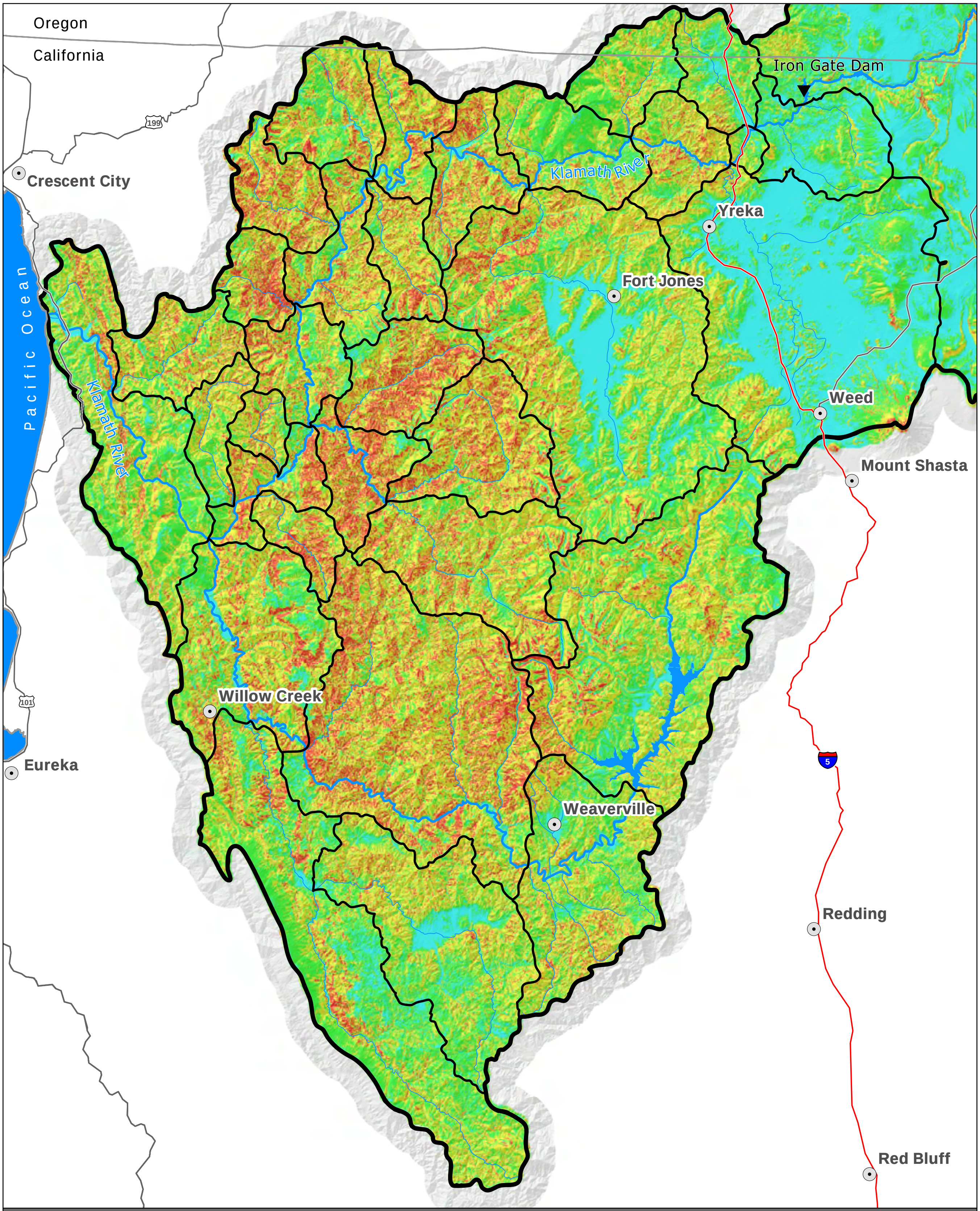
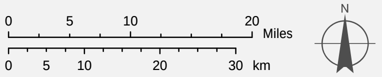


FIGURE 4 Hillslope Gradient Classes in the Lower Klamath Basin

Slope Categories

- 🟦 0-15%
- 🟩 15-35%
- 🟨 35-65%
- 🟥 >65%



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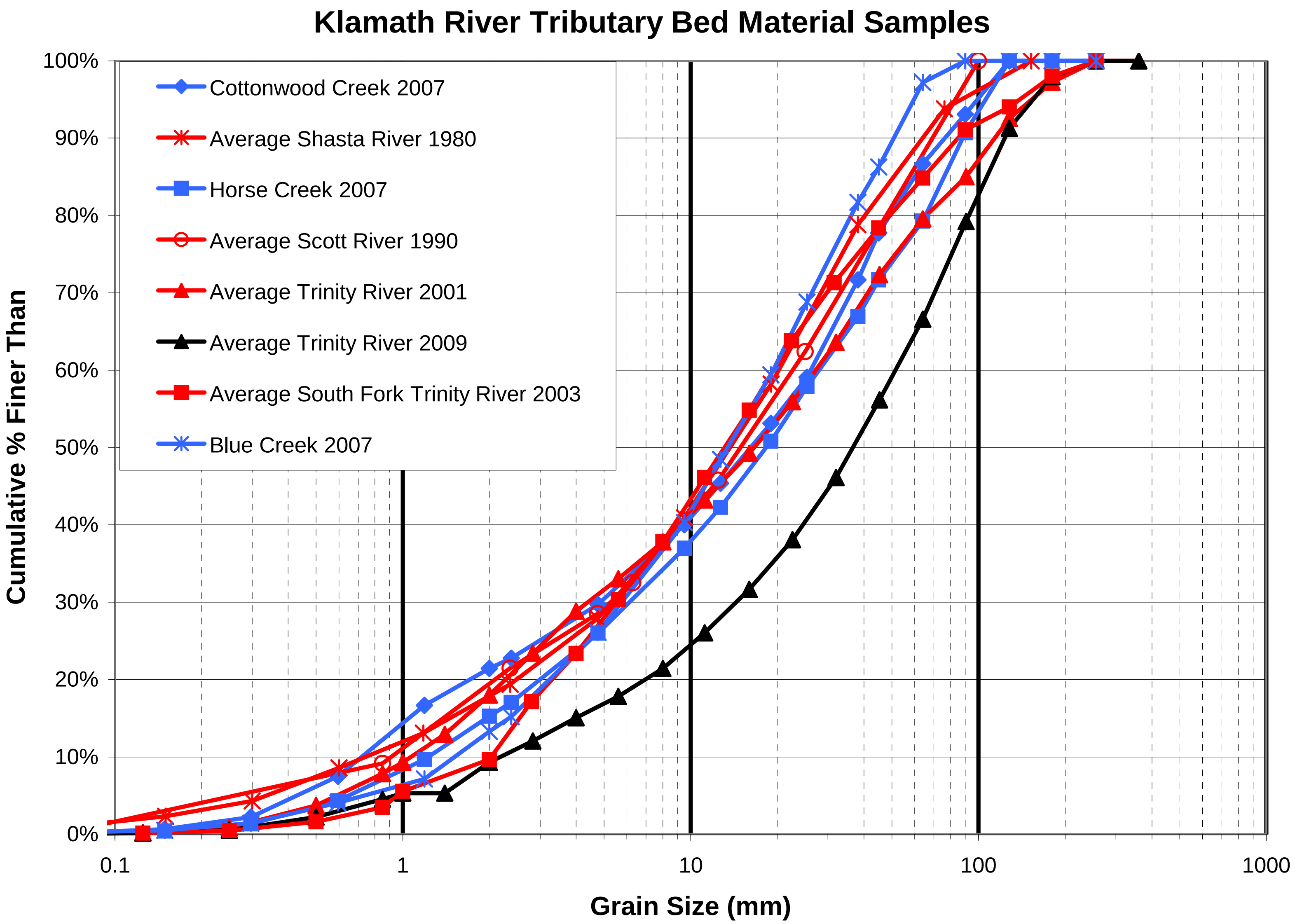


Figure 5. Grain size distributions for bed material bulk samples from Klamath River tributaries.

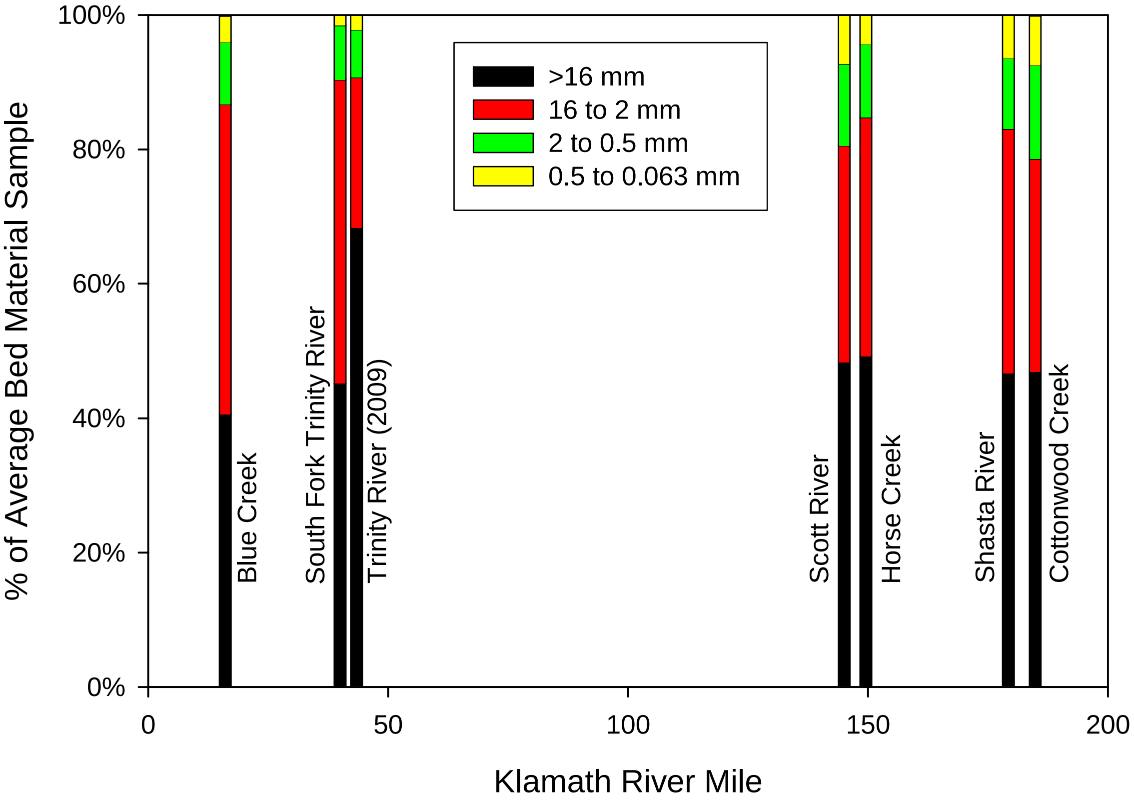


Figure 6. Coarse sediment fractions of bed material bulk samples for Klamath River tributaries.

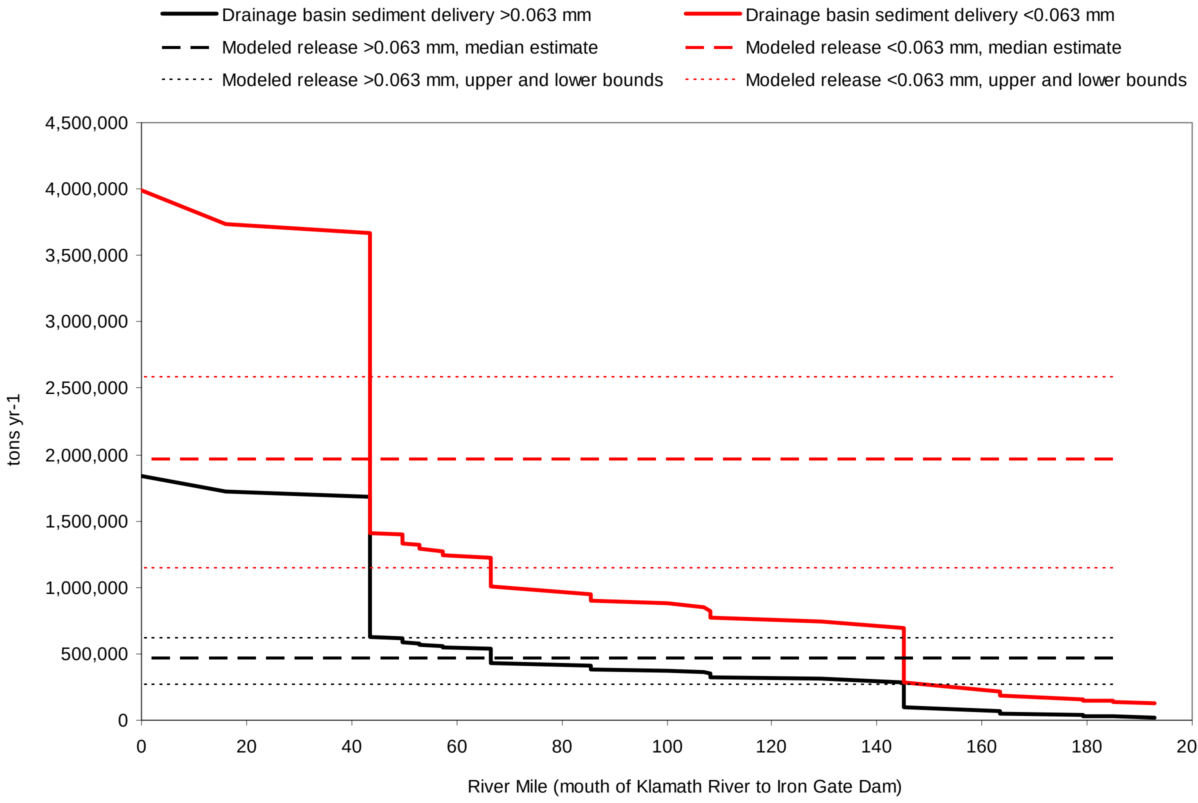


Figure 7. Modeled sediment release from dam removal and cumulative average annual sediment delivery from the basin to the Klamath River between Iron Gate Dam and the mouth.

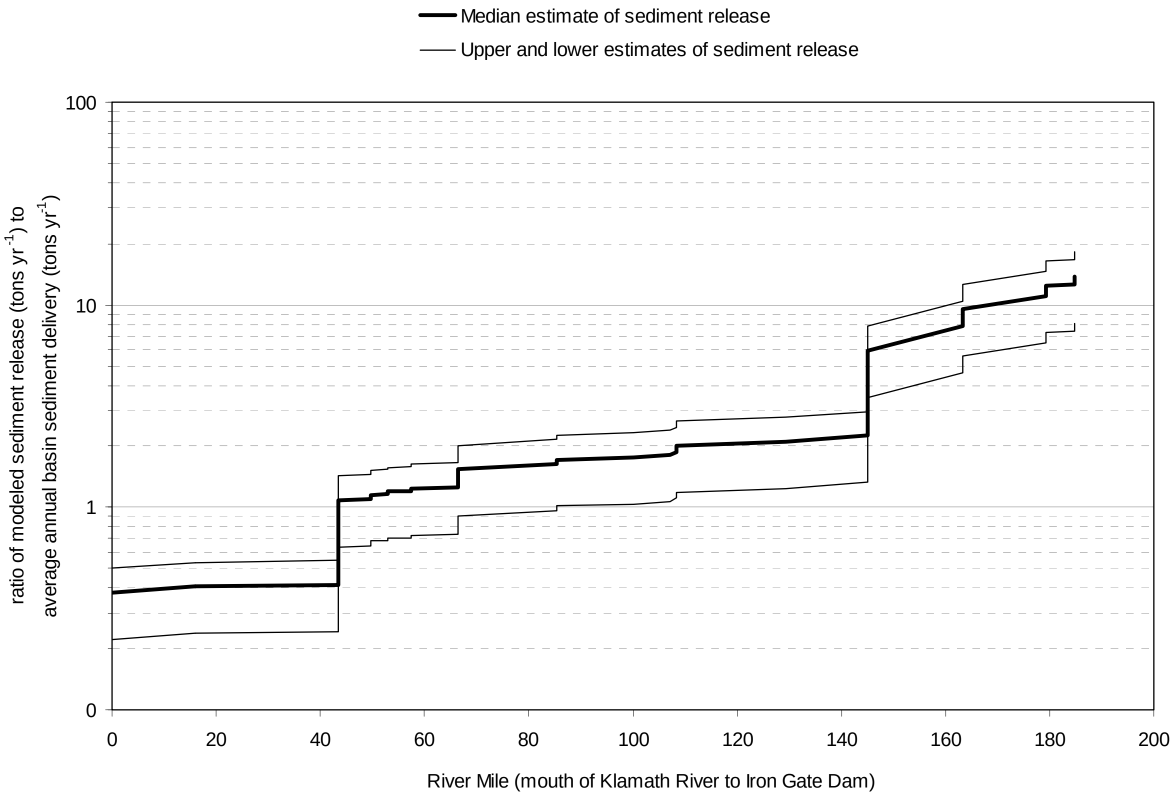
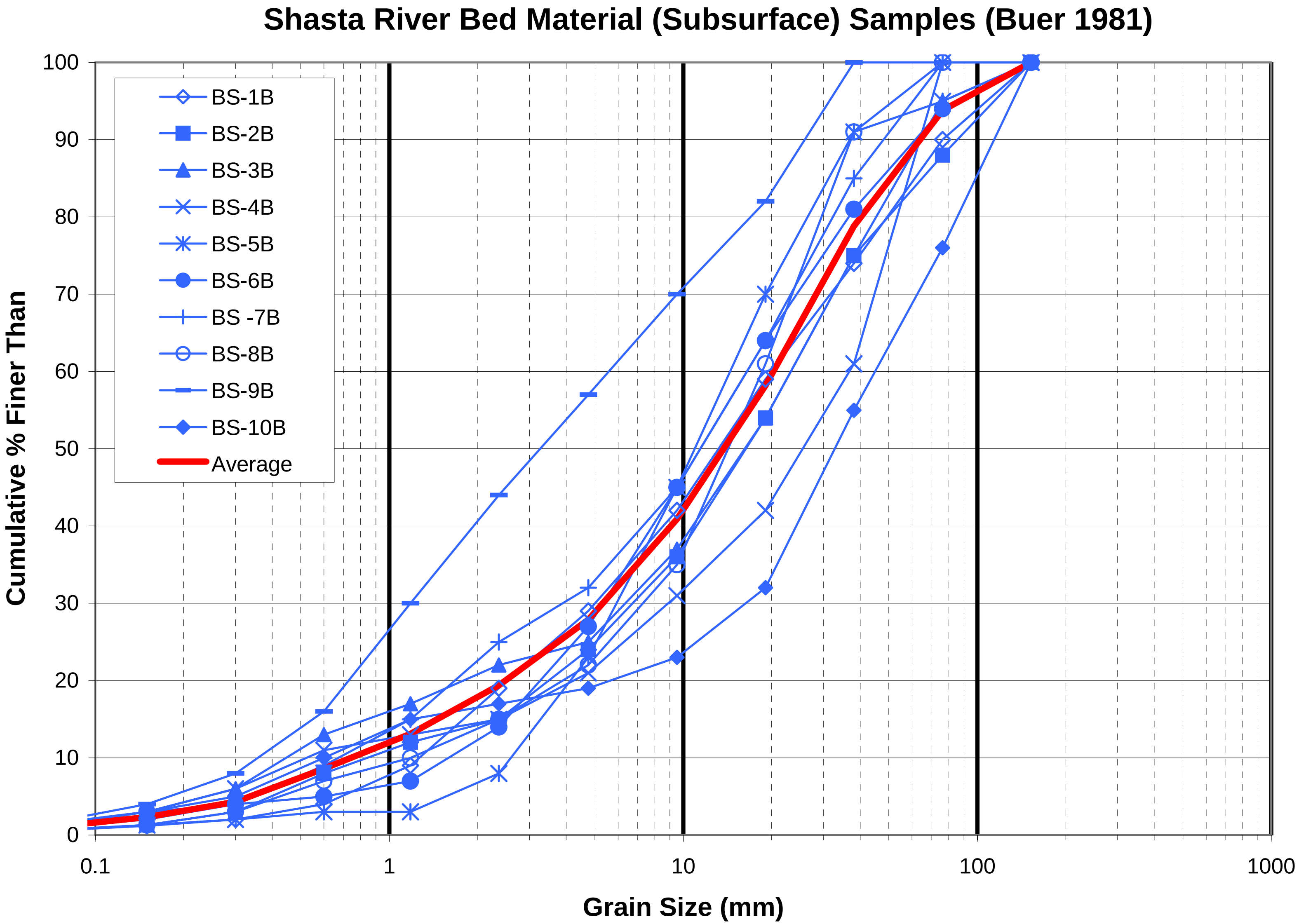


Figure 8. Ratio of modeled sediment release from dam removal to cumulative average annual basin sediment delivery.

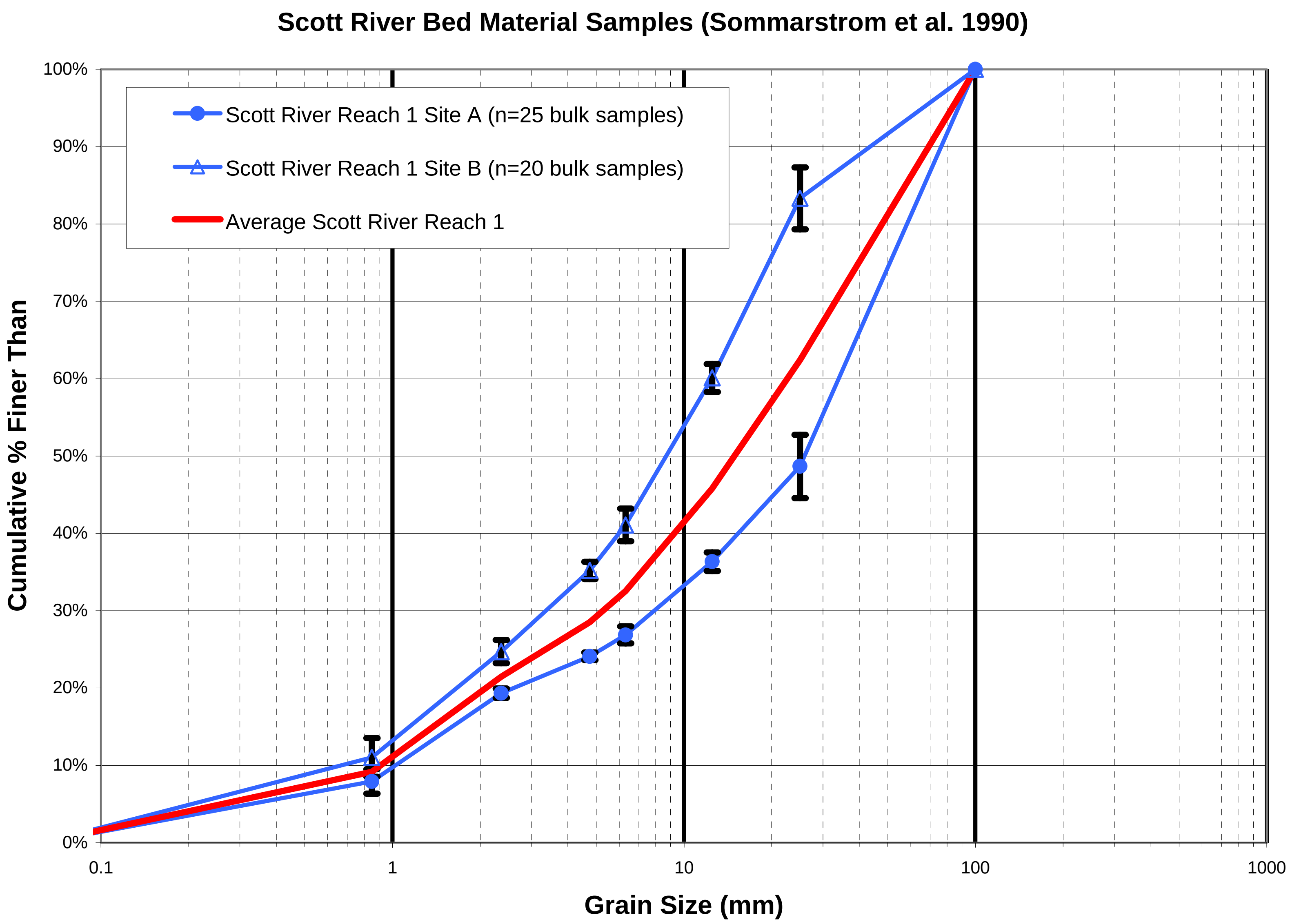
Appendices

Appendix A

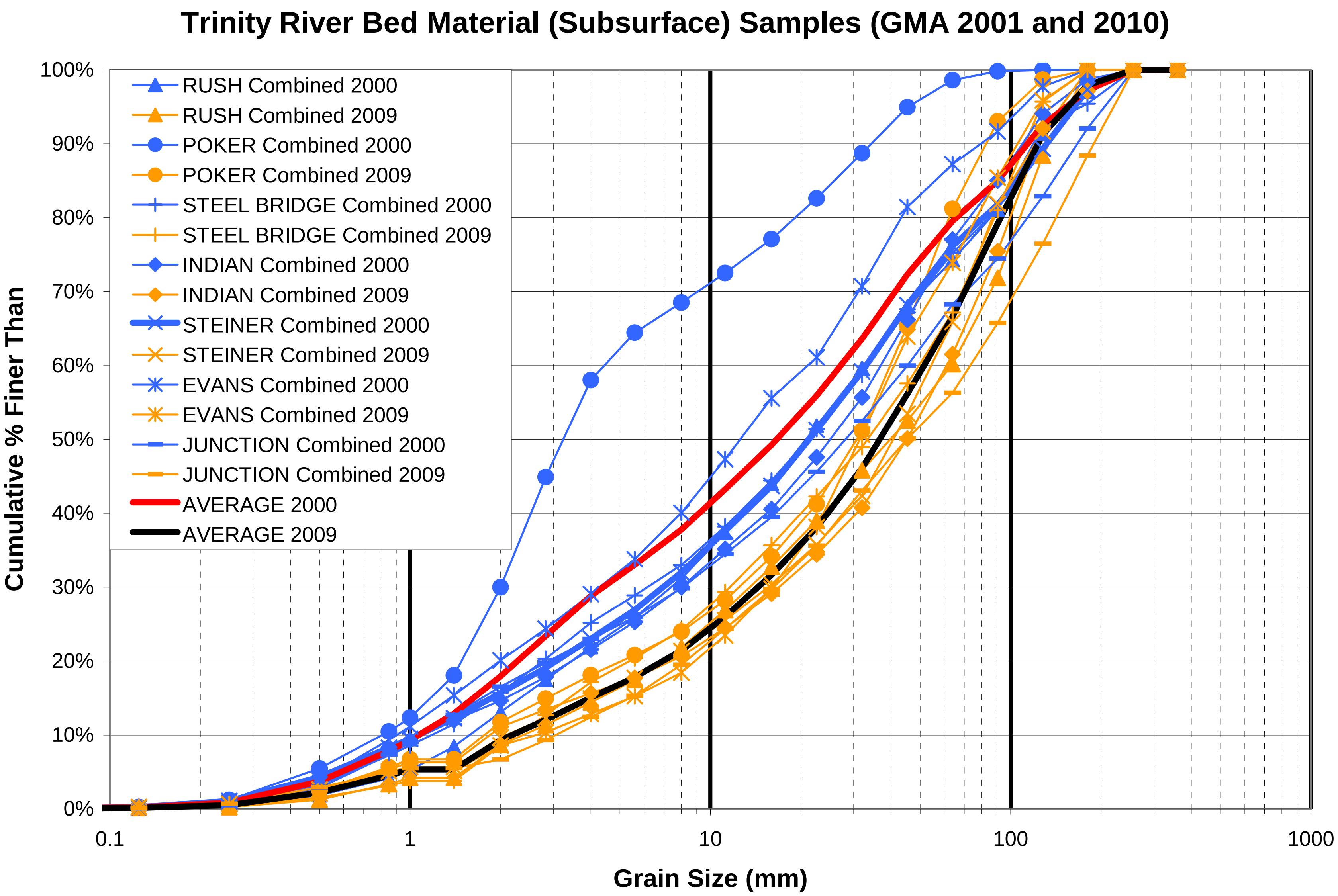
Bed Particle Size Distributions for Bulk Samples Taken from the Shasta River, Scott River, and Trinity River



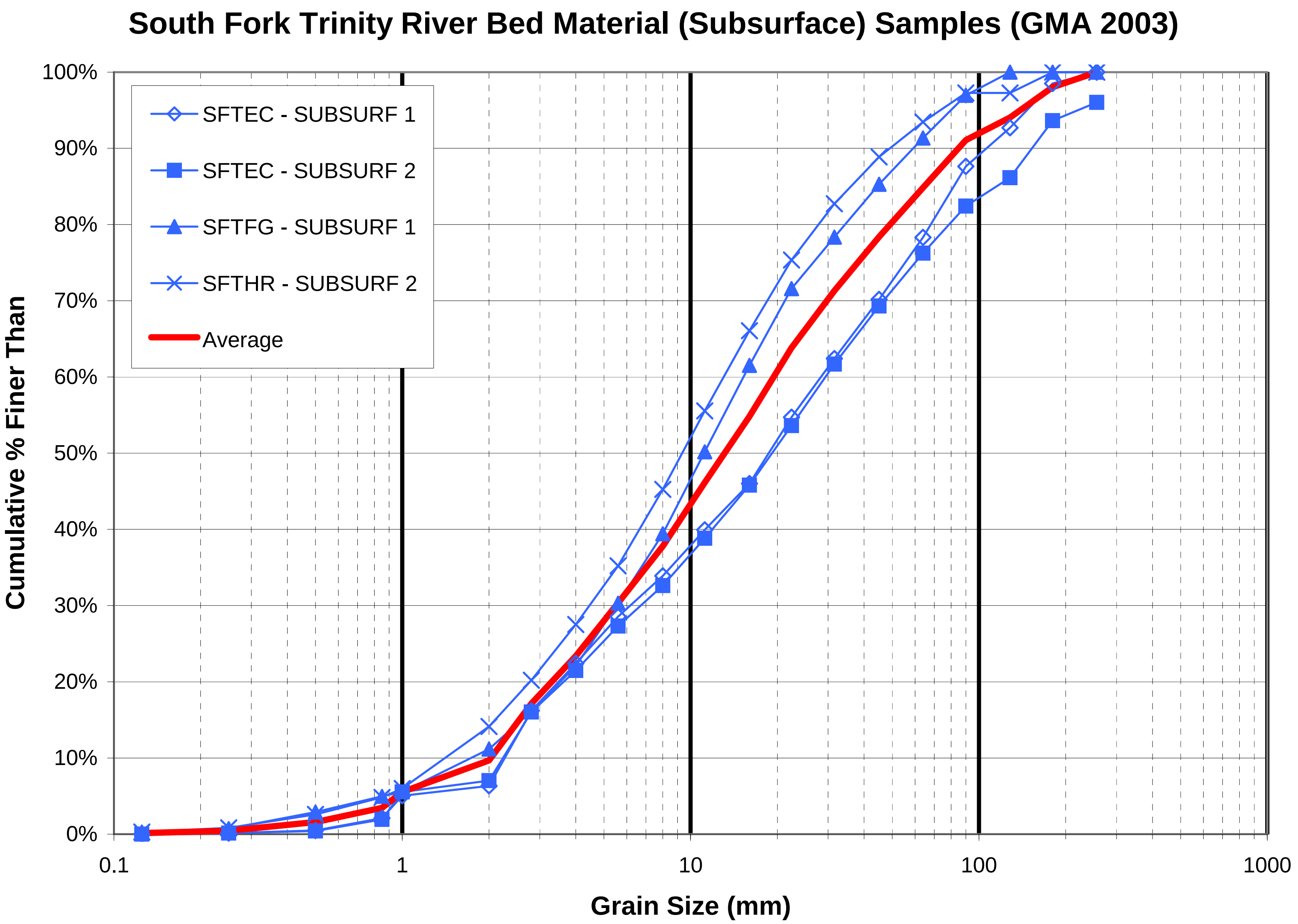
Appendix A Figure 1. Grain size distributions for Shasta River subsurface samples (Buer 1981).



Appendix A Figure 2. Grain size distributions for bed material samples from Reach 1 on the Scott River (Sommarstrom et al. 1990); error bars represent 95% confidence intervals.



Appendix A Figure 3. Grain size distributions for subsurface samples collected in 2000 and 2009 on the Trinity River between Lewiston Dam and Junction City (GMA 2001 and 2010).



Appendix A Figure 4. Grain size distributions for subsurface samples collected in 2000 and 2009 on the Trinity River between Lewiston Dam and Junction City (GMA 2001 and 2010).

Appendix B

Extrapolation of Sediment Delivery in Source Areas Where Information is Missing or Incomplete

Table B-1. Extrapolation of sediment delivery to connected source areas in the Shasta basin not included in the 2004 cumulative watershed effects analysis of the Klamath National Forest.

Generalized geology	Slope	Source area (mi^2)	Delivery rate (tons km^{-2} yr^{-1})	Delivery (tons yr^{-1})
Ice and water	>65%	0	0	0
	0-15%	0.0	0	0
	15-35%	0.0	0	0
	35-65%	0	0	0
Igneous intrusive	>65%	0.3	220	62
	0-15%	0.4	0	0
	15-35%	3.1	0	0
	35-65%	4.0	120	480
Metamorphic (hard)	>65%	2.2	224	483
	0-15%	18.7	0	0
	15-35%	37.6	0	0
	35-65%	49.5	120	5,943
Metamorphic (soft)	>65%	0.1	490	47
	0-15%	1.3	0	0
	15-35%	3.0	120	365
	35-65%	4.0	220	890
Older volcanics (pre-Quaternary)	>65%	0.1	60	7
	0-15%	64.9	0	0
	15-35%	26.9	0	0
	35-65%	7.9	60	475
Sedimentary	>65%	0.1	220	26
	0-15%	2.3	0	0
	15-35%	2.0	0	0
	35-65%	0.9	120	110
Unconsolidated surficial deposits	>65%	0.0	220	6
	0-15%	133.4	0	0
	15-35%	8.0	0	0
	35-65%	1.9	120	234
Total		372.9		9,128

Table B-2. Extrapolation of sediment delivery to Red Cap Creek, Camp Creek, and Bluff Creek (watersheds not included in the Lower-Middle Klamath Watershed Analysis by Six Rivers National Forest).

Sub-basin	Generalized geology	Geologic unit			Source area (mi^2)	Delivery rate (tons mi-2 yr^{-1})	Delivery (tons y^{-1})
Camp Creek	Igneous intrusive	Western Paleozoic and Triassic	Rattlesnake Creek	gabbro	0.1	232	16
				plagiogranite	0.7	232	171
	Metamorphic hard	Western Klamath	Galice	metasediments	32.8	1,280	42,014
				serpentinite	1.3	1,410	1,894
			Rogue	metavolcanic	0.0	1,410	41
		Western Paleozoic and Triassic	Rattlesnake Creek	chert	0.1	232	22
				metasediments	1.5	232	354
				metavolcanic	4.2	232	984
				peridotite	1.1	232	257
Camp Creek Subtotal					42.0	na	45,754
Red Cap Creek	Igneous intrusive	(Blank)	Ironside Mountain	diorite	10.4	1,003	10,422
			unnamed	aplite	0.4	1,003	434
				gabbro	2.2	1,003	2,169
	Metamorphic hard	Western Klamath	Galice	metasediments	17.8	1,280	22,766
			Rogue	metavolcanic	0.2	1,410	255
		Western Paleozoic and Triassic	Rattlesnake Creek	peridotite	3.2	232	733
			Sawyers Bar	metasediments	4.1	207	855
				metavolcanic	1.0	207	210
				peridotite	0.1	232	26
			Western Hayfork	metavolcanic	23.7	207	4,905
Red Cap Creek Subtotal					63.1	na	42,775
Bluff Creek	Igneous intrusive	Western Klamath	undifferentiated	diorite	2.3	1,003	2,332
	Metamorphic hard	Eastern Franciscan	Bluff Creek	metasediments	2.9	1,280	3,723
		Western Klamath	Galice	metasediments	29.0	1,280	37,053
				serpentinite	7.5	1,410	10,582
			Josephine Ophiolite	peridotite	5.1	232	1,180
			Rogue	metavolcanic	3.6	1,410	5,094
	Metasediment soft	Eastern Franciscan	Pickett Peak	schist quartz mica	23.7	1,717	40,700
	Sedimentary	Eastern Franciscan	undifferentiated	graywacke	0.0	207	5
Bluff Creek Subtotal					74.1	na	100,668
Total					179.2	na	189,197