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FINE-SEDIMENT LOADINGS TO LAKE TAHOE[1]

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ABSTRACT: Over the past 35 years, a trend of decreasing water clarity has been documented in Lake Tahoe, attributable in part to the delivery of fine-grained sediments emanating from upland and channel sources. The overall objective of the research reported here was to determine the amount of fine sediment delivered to Lake Tahoe from each of the 63 contributing watersheds. The research described in this report used combinations of field-based observations of channel and bank stability with measured and simulated data on fine-sediment loadings to estimate fine-sediment loadings from unmonitored basins throughout the Lake Tahoe Basin. Loadings were expressed in the conventional format of mass per unit time but also in the number of particles finer than 20 μm, the latter for future use in a lake-clarity model. The greatest contributors of fine sediment happened to be those with measured data, not requiring extrapolation. In descending order, they are as follows: Upper Truckee River [1,010 tonnes per year (T/year)], Blackwood Creek (846 T/year), Trout Creek (462 T/year), and Ward Creek (412 T/year). Summing estimated values from the contributing watersheds provided an average, annual estimate of fine-sediment (<0.063 mm) loadings to the lake of 5,206 T/year. A total of 7.79E + 19 particles in the 5-20 μm fraction were calculated to enter Lake Tahoe in an average year with the Upper Truckee River accounting for almost 25% of the total. Contributions from Blackwood, Ward, Trout, and Third creeks account for another 23% of these very fine particles. Thus, these five streams making up about 40% of the basin area, account for almost 50% of all fine-sediment loadings to the lake. Contribution of fine sediment from streambank erosion were estimated by developing empirical relations between measured or simulated bank-erosion rates with a field-based measure of the extent of bank instability along given streams. An average, annual fine-sediment loading from streambank erosion of 1,305 T/year was calculated. This represents about 25% of the average, annual fine-sediment load delivered to the lake from all sources. The two largest contributors, the Upper Truckee River (639 T/year) and Blackwood Creek (431 T/year), account for slightly more than 80% of all fines emanating from streambanks, representing about 20% of the fine sediment delivered to Lake Tahoe from all sources. Extrapolations of fine-sediment loadings to the unmonitored watersheds are based on documented empirical relations, yet contain a significant amount of uncertainty. Except for those values derived directly from measured data, reported results should be considered as estimates.

(KEY TERMS: sediment; fluvial processes; lakes; turbidity; bank erosion.)

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INTRODUCTION

The Lake Tahoe Basin has a long history of human interaction and exploitation dating back to the 1850s. Activities such as logging, road construction, mining, overgrazing, and urbanization have led to degradation of land and water resources and threaten to do irreparable damage to the lake. In particular are concerns over lake clarity, which have been partly attributed to the delivery of fine-grained sediment emanating from upland, urban, and channel sources. Over the past 35 years, a trend of decreasing water clarity, as measured by secchi depth, has been documented (Goldman, 1988).

A number of studies have been completed in the past 30 years to address sediment delivery issues from various watersheds in the Lake Tahoe Basin. Most of these studies have each focused on only a few streams within the watershed (Kroll, 1976; Glancy, 1988; Nolan and Hill, 1991; Stubblefield, 2002). Recent work by Reuter and Miller (2000), Rowe *et al.* (2002), and Simon *et al.* (2003) used suspended-sediment transport data from the Lake Tahoe Interagency Monitoring Program, which brought together data from streams all around the watershed. These works have indicated that the following streams are among the largest contributors of suspended sediment to Lake Tahoe: Incline, Third, Blackwood, and Ward creeks, and the Upper Truckee River. Most of the sediment is delivered during the spring snowmelt period (predominantly May and June), which correlates well with the spring reduction in secchi depth. Because lake clarity is related to the very fine particles that remain in suspension and that transport adsorbed constituents, it is essential to identify the magnitude and source of these fine-grained materials. Selection of appropriate management strategies must be founded on the identification of the controlling processes and associated source areas of fine sediment. These source areas can be broadly separated into uplands, urban areas, and channels. More specifically, upland sources may include slopes, fields, roads, construction-site gullies etc., while channel sources may include channel beds, bars, and streambanks. Moreover, the magnitude of sediment production, transport, and delivery to the lake varies widely across the basin as a function of differences in precipitation, surficial geology, land use/land cover, and channel instabilities.

The term *fine sediment* can be defined in several ways based on how the threshold diameter is defined. In sediment-transport analyses, fine sediment is generally considered to be those particles finer than 0.063 mm whose transport is not a function of size and weight, but of availability to flow. This threshold represents the distinction between sand- and silt-sized particles. Coarser sediments are hydraulically controlled with entrainment being a function of the energy, stream power, or shear stress of the flow relative to the size and weight of the particle. With regards to lake clarity, however, it is the finest particles that are of the greatest interest because they tend to stay in suspension for extended periods of time. Thus, *fine sediment* can also be considered as those particles finer than 0.020 mm, representing the distinction between silt- and clay-sized particles.

Suspended-sediment loadings to Lake Tahoe from selected watersheds were reported by Rowe *et al.* (2002) and by Simon *et al.* (2003). Both reports identified streams such as Blackwood, Trout, Third and Ward creeks, and the Upper Truckee River as major contributors of suspended sediment. Using suspended-sediment particle-size data from the U.S. Geological Survey (USGS), which distinguishes between particles coarser or finer than 0.063 mm, Simon *et al.* (2003) provided initial estimates of fine-sediment loads in tonnes per year (T/year) and yields (T/year/km^2) from 14 streams around the basin. This study also highlighted important distinctions in sediment production from different sides (quadrants) of the basin and from different sources. With extensive reconnaissance-level field work throughout the basin and by resurveying monumented cross sections originally established in the 1980s (Hill *et al.*, 1990), streambank erosion was identified as an important source of suspended sediment from several watersheds, including Blackwood and Ward creeks, and the Upper Truckee River.

Estimates of fine-sediment loadings from all contributing watersheds and particularly from streambank sources are required to (1) validate estimates of fine-sediment loadings being simulated by others using a watershed model and (2) effectively simulate current and future water-clarity conditions in Lake Tahoe using a lake-clarity model.

The research undertaken and described in this report is only one of numerous projects being conducted by academic institutions, government agencies, and private firms to improve knowledge about the causes and consequences of declining lake clarity. A synthesis of the products generated from all of this research and development of a TMDL for Lake Tahoe will rely heavily on numerical simulations of lake clarity being conducted by the University of California, Davis. The reliability of this modeling effort is, in part, a function of the quality of the data provided to the modelers from various sources. Data on flow and sediment inputs, and water temperature are critical.

Whereas most sediment-transport studies express loadings in units of mass (such as Megagrams or

tonnes) or volume (such as cubic meters), the lake clarity model requires loadings in *numbers of particles*. An important data-collection program conducted by the University of California, Davis and the USGS has recently provided fine particle-size data in the 0.005-0.020 mm (5-20 μm) range (Rabidoux, 2005). These data provide a means by which to calculate the number of particles in this important size class that is transported to Lake Tahoe from the sampled streams. The Rabidoux (2005) dataset, in combination with suspended-sediment transport relations, measured and simulated rates of streambank erosion, and semi-quantitative evaluations of the relative stability of stream channels throughout the basin (Simon *et al.*, 2003) provide the means to estimate fine-sediment loadings from all watersheds draining to Lake Tahoe.

The overall objective of the research reported here was to determine the amount of fine sediment delivered to Lake Tahoe from each of the 63 contributing watersheds (Figure 1). Because the watershed modeling being conducted by others does not account for channel processes, a second critical objective was to provide estimates of stream-channel contributions, particularly fine sediment emanating from streambank erosion. This was also to be accomplished for each contributing watershed. More specifically, this study aimed to provide three forms of fine-sediment loadings data for each contributing stream in the Lake Tahoe Basin: (1) average, annual fine-sediment (<0.063 mm) loadings in T/year; (2) average, annual fine-sediment (<0.020 mm) loadings in number of particles per year (*n*/year); and (3) average, annual fine-sediment (<0.063 mm) loadings in T/year from streambank erosion.

Extrapolations of fine-sediment loadings to the unmonitored watersheds are based on documented empirical relations, yet contain a significant amount of uncertainty. Except for those values derived directly from measured data, reported results should be considered as estimates. In addition, loadings information from intervening zones and from shoreline erosion (Taylor, 2002) was not considered.

RESEARCH APPROACH

A large amount of useful data on flow, suspended sediment, and channel characteristics were available from previous studies conducted in the Lake Tahoe Basin (Jorgensen *et al.*, 1978; Hill *et al.*, 1990; Nolan and Hill, 1991; Rowe *et al.*, 2002; Simon *et al.*, 2003; Rabidoux, 2005). Still, without resources to conduct detailed numerical simulations of channel processes for each stream as was done for the Upper Truckee River, and Ward and General creeks (Simon *et al.*, 2003), a combination of empirical methods was required to address the study objectives. An approach that was used successfully by Simon *et al.* (2003) to initially sort streams by similar basin characteristics was the concept of basin quadrants.

In the Lake Tahoe Basin, precipitation, geology, and other basin characteristics vary from one side of the lake to the other resulting in a broad range of sediment-transport rates. Granitic materials dominate the eastern part of the basin, whereas glacial and volcanic materials share dominance with the granitics on the west side (Figure 2). Volcanics dominate the northern part of the basin. Urban areas are generally found in the north and south at elevations near the lake. Alluvium is found mostly in the larger streams in the southern part of the basin (Trout Creek and the Upper Truckee River). In particular, mean-annual precipitation varies widely from the relatively dry eastern side (500-1000 mm) to the wetter (1000-2000 mm) on the western side (Figure 2) (Sierra Hydrotech, 1986). To partially account for these differences and to make interpretations of differences in suspended-sediment loads and yields to Lake Tahoe, watersheds were separated into the four principle directional quadrants; north, south, east, and west (Figure 3). Streams referred to as "northern" include First, Second, Third, and Incline creeks. The major "southern" streams are the Upper Truckee River and Trout Creek. "Eastern" streams include Edgewood, Glenbrook, and Logan House creeks, while "western" streams include Blackwood, Ward, and General creeks.

Existing Suspended-Sediment Transport Data and Relations for Fine Sediment

Determination of fine-sediment (<0.063 mm) loadings (in T/year) was straightforward for streams with historical flow, concentration, and particle-size data. The methods employed, and results are presented and mapped in detail in Simon *et al.* (2003) and a summary is provided here. Raw suspended-sediment concentration and associated instantaneous discharge data was obtained from the USGS and used to develop relations between concentration and discharge and then, load and discharge in log-log space. Transport relations were checked to discern any shifts over time due to land disturbance or variations in runoff over the period. In some cases, more than one relation was used for a particular station Simon *et al.*, 2003). Using additional data for each site from the USGS, similar relations were established between discharge and the percentage of suspended sediment finer than 0.063 mm. The suspended-sediment load

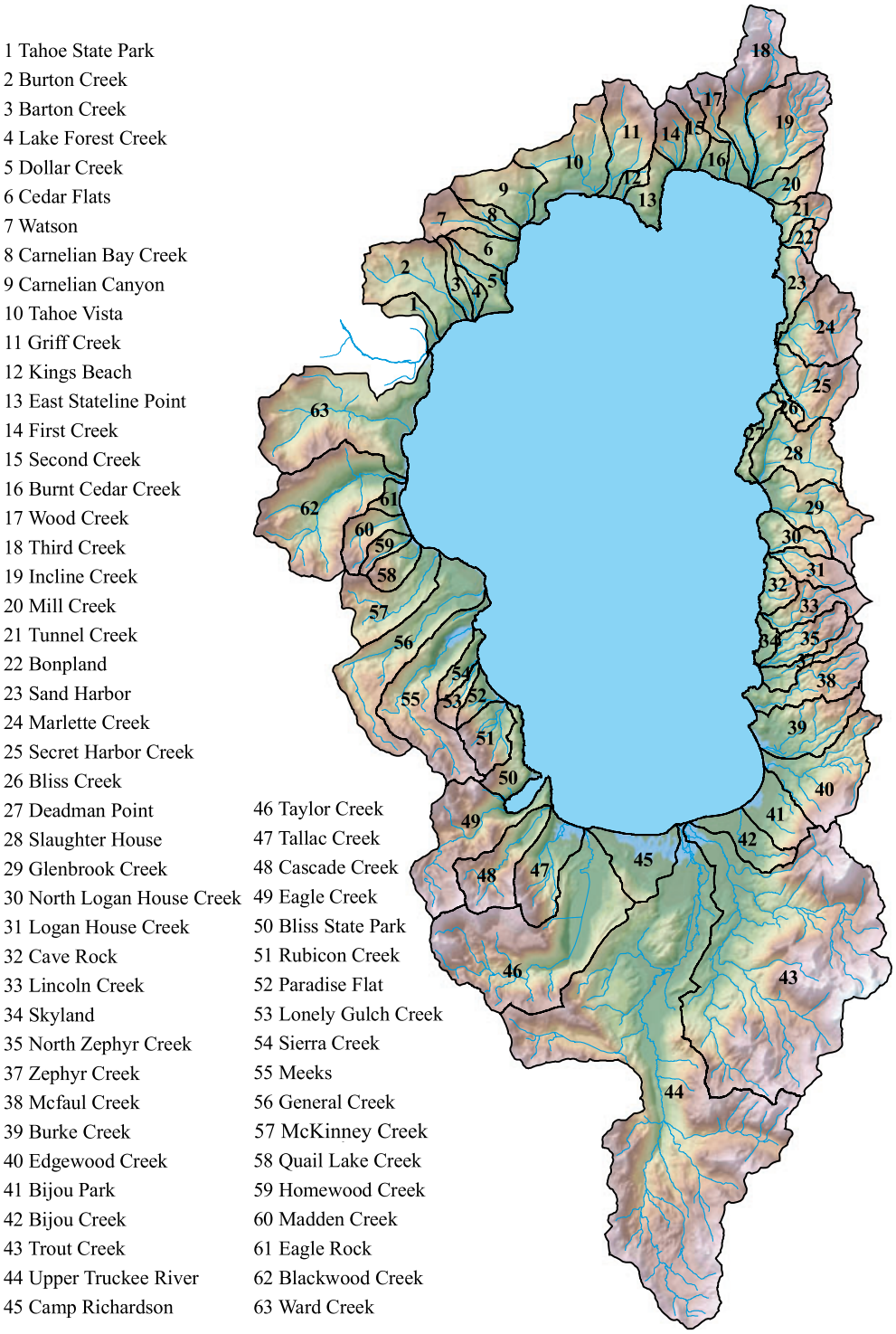

FIGURE 1. Map of the Lake Tahoe Basin Showing the 63 Watersheds Draining to the Lake.

for each day of record was then obtained by substituting the mean-daily discharge into the sediment-transport relation. Fine-sediment loading for each day was calculated by again substituting the discharge into percent fines-discharge relation and multiplying the derived percentage by the total suspended load for that day. All days for a given year were summed to create annual, suspended-sediment loads for each year of record. Median and average, annual values were then calculated from the annual loadings data.

Results for index sites are reproduced here in Table 1 with their period of record in Table 2. The

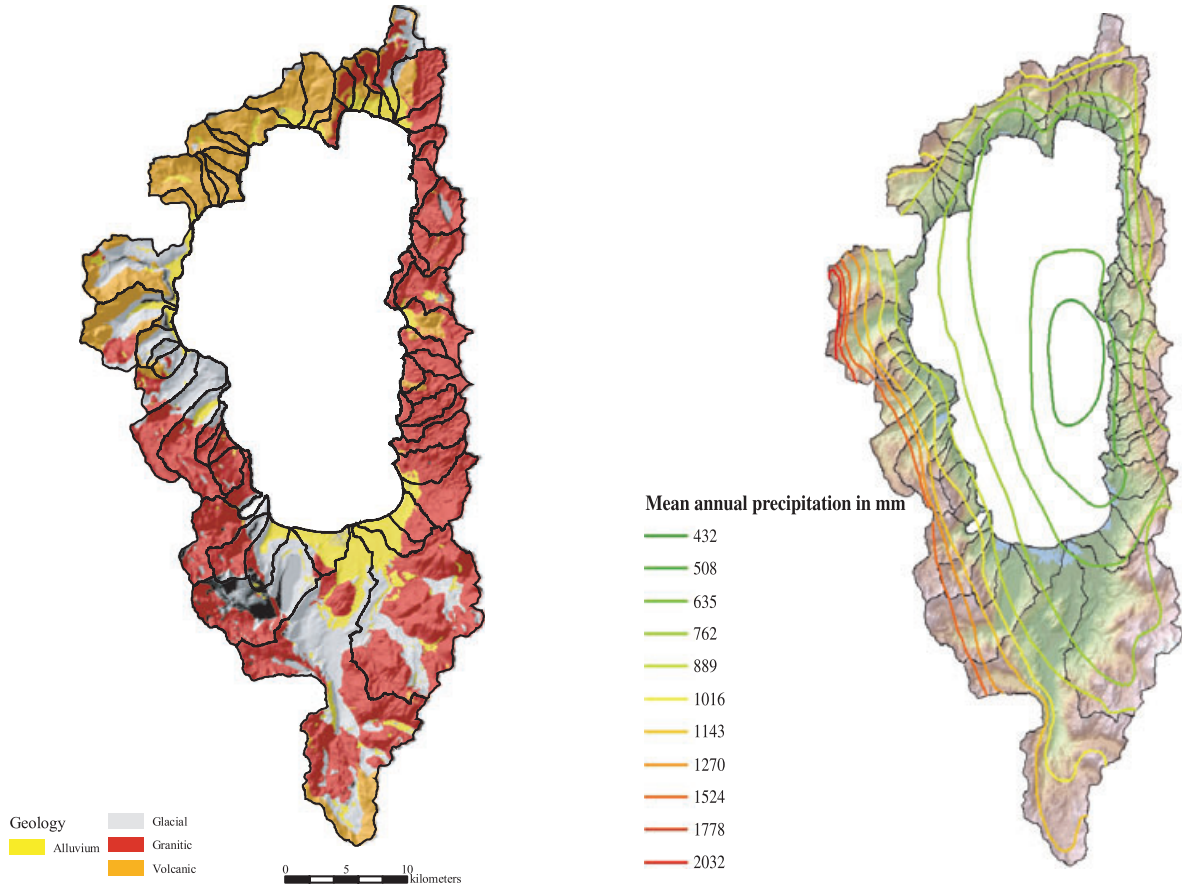

FIGURE 2. Surficial Geology (left) and Mean-Annual Precipitation (right) of the Lake Tahoe Basin. Bases from USGS (1994). Precipitation data from Sierra Hydrotech, (1986).

concept of an index station is that sediment loadings and yields from a particular watershed to Lake Tahoe can be represented by sediment-transport data from a specific downstream location in that watershed. Selections of these stations were based on two criteria: (1) the station from a given stream with the longest period of record and (2) the station was a downstream location. These stations were then used to interpret similarities and differences in sediment delivery to the lake.

The rationale that was used to extrapolate suspended-sediment loadings from streams with measured data to streams without historical data was based on the concepts of basin quadrants and relative channel stability. The idea behind this approach was that streams exhibiting similar attributes of channel stability within a zone of similar precipitation, geology, land use, and topographic characteristics would yield similar amounts of sediment per unit area. In contrast, stable and unstable streams from the same zone would have markedly different sediment yields. Thus differences in stability can be used to differentiate suspended-sediment yields from similar areas, zones, or regions. This concept has been used successfully to determine "background" or "natural" rates of suspended-sediment transport rates, and to distinguish between stable and unstable streams for ecoregions across the United States (Simon *et al.*, 2004).

Because streams draining larger basin areas in a given quadrant and condition will tend to transport more sediment than smaller ones, loadings data from the index streams were divided by basin area to establish fine-grained (<0.063 mm) suspended-sediment yields (in T/year/km^2). The distribution of yield data (10th, 25th, 50th, 75th, and 90th percentiles) was then calculated by basin quadrant (Table 3).

Channel Conditions and Rapid Geomorphic Assessments

Evaluation of relative channel stability was accomplished using rapid geomorphic assessments (RGAs) of stream-channel conditions and identification of the dominant geomorphic processes, extent of channel

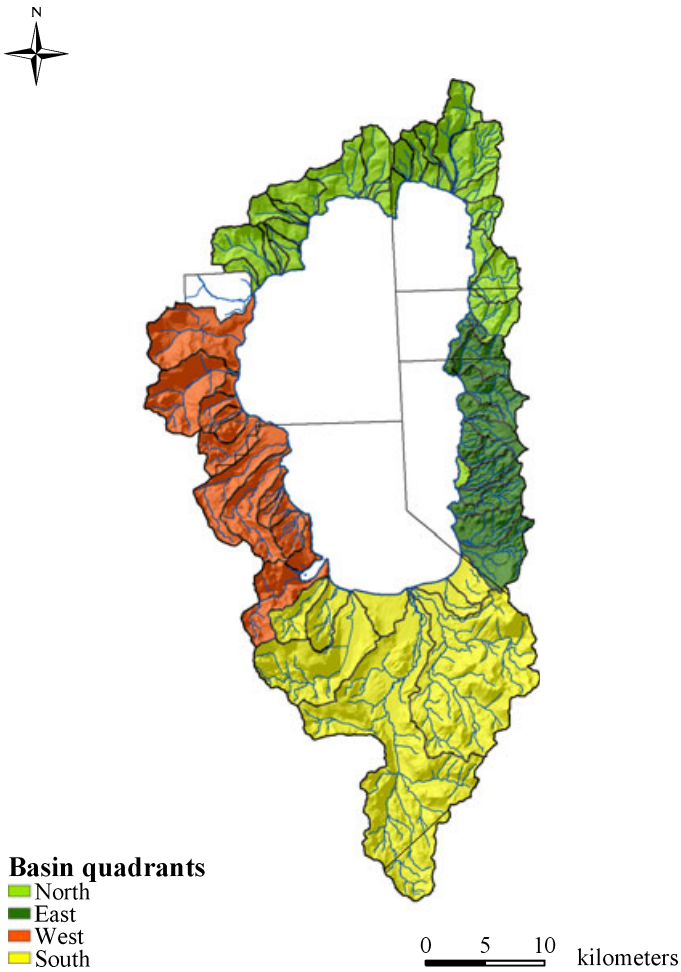

FIGURE 3. Map of the Lake Tahoe Watershed Showing Designation of Four Basin Quadrants.

instabilities, and stage of channel evolution (Simon, 1989) (Figure 4). As part of the RGA procedure, a semi-quantitative channel-stability index was modified to include potential side-slope erosion (combined-stability index) and calculated for hundreds of sites along the studied streams based on diagnostic criteria obtained during each RGA. Higher index values indicate greater instability. In addition, samples of bed and bank material were obtained at most of the RGA sites and are reported in Simon *et al.* (2003). Particle-size analysis of these samples were used for determining the amount of fine-grained sediment (<0.063 mm) in the boundary materials (Figure 5). About 300 RGAs were conducted during 2002 and an additional 53 RGAs were conducted in 2004 as part of this study to fill gaps in the data network. Combined stability-index data collected during RGAs were averaged for each stream and sorted by basin quadrant (Table 4). The range and distribution of values were then calculated for each quadrant (Table 5).

Estimates of Fine-Sediment Loadings: T/year < 0.063 mm

Initial analysis of fine-sediment (<0.063 mm) loadings in T/year to Lake Tahoe from all 63 watersheds (with the exception of intervening zones) were conducted using the distributions of fine-sediment yields and the combined-stability index, and applied to streams with no historical loadings data. The procedure was as follows:

1. Determine the average, combined stability index for the stream (Table 4).
2. Calculate the distribution of average values by basin quadrant (10th, 25th, 50th, 75th, and 90th percentiles) (Table 5).
3. For a given stream, use the appropriate percentile class based on the combined-stability index distribution, and apply to the same percentile of the distribution of fine-grained (<0.063 mm) suspended-sediment yield (Table 3).
4. Obtain the fine-grained (<0.063 mm) suspended-sediment yield from the table and multiply by basin area to obtain average, annual fine-sediment load in T/year.

On average, approximately 5,200 T/year of fine (<0.063 mm) sediment is delivered to Lake Tahoe from the 63 contributing watersheds. Loadings from the north, south, and west quadrants are similar, with contributions representing 32, 37, and 30%, respectively. Results are mapped in Figure 6 showing annual fine-sediment loadings in T/year and the percent contribution to the lake.

Estimates of Fine-Sediment Particle Flux: n/year < 0.020 mm

The fundamental approach to developing estimates of basinwide fine-particle flux to Lake Tahoe was based on similar techniques to those used above. That is, using distributions of particle flux by basin quadrant from measured data and regression relations, and then applying those relations to streams with no fine-particle flux data. Particle flux is defined as the product of the concentration of particles per volume of water times the flow rate

$$n = CQ\alpha, \tag{1}$$

where n is particle flux, the number of particles per second, C is concentration in mg/l, Q is discharge in ft^3/s, and α is factor to convert from per milliliter to per ft^3.

TABLE 1. Annual Fine-Sediment Loadings (<0.063 mm) Derived From Measured Data for Index Stations.

Stream	Station Number	Annual Fine Load Average (tonnes)	Annual Fine Load Median (tonnes)	Contribution of Fines (%)	Years of Data	Drainage Area (km^2)
UTR	10336610	1261	1010	44	24	142
Blackwood	10336660	1347	846	45	40	29.0
Trout	10336780	624	462	38	40	95.1
Ward	10336676	658	412	47	28	25.1
Third	10336698	462	318	31	26	15.7
Incline	10336700	320	129	67	17	18.1
General	10336645	69.2	53.3	29	20	19.3
Eagle[1]	10336630		21.8		3	20.4
Meeks[1]	10336640		19.1		3	22.2
Edgewood	103367585	12.9	11.4	59	11	8.1
Glenbrook	10336730	8.8	7.0	80	16	10.5
Quail Lake[1]	10336650		3.2		3	4.2
Dollar [1]	10336684		2.6		3	4.7
Logan House	10336740	3.5	2.3	75	17	5.4

Notes: Modified from Simon *et al.*, 2003).
[1]Data from Kroll (1976).

TABLE 2. Period of Record for Index Stations.

Stream	USGS Station Number	Basin Quadrant	Distance Above Mouth (km)	Period of Record (year)
Third	10336698	N	0.19	26
Incline	10336700	N	0.27	17
Trout	10336780	S	4.52	40
Upper Truckee	10336610	S	2.94	24
Edgewood	103367585	E	3.81	11
Glenbrook	10336730	E	0.04	16
Logan House	10336740	E	0.66	17
Eagle Rock	103367592	E	2.99	10
Blackwood	10336660	W	0.31	40
General	10336645	W	0.65	20
Ward	10336676	W	0.44	28

TABLE 3. Distributions of Annual Fine-Sediment (<0.063 mm) Yields (in T/year/km^2) for the Four Basin Quadrants Calculated From All Index Stations in Each Quadrant.

Percentiles (T/year/km^2) 10th	25th	50th	75th	90th	Quadrant
0.46	0.55	0.70	1.05	1.26	E
1.87	3.83	7.10	13.65	17.58	N
5.12	5.45	6.00	6.55	6.88	S
0.81	0.91	1.93	13.0	18.95	W

Rabidoux (2005) used relations between flow discharge and particle flux to develop loadings estimates for sites with measured fine-particle data. The number of samples for each stream is shown in Table 6. It is recognized that particle-size distributions of suspended sediment change over time and space. Distributions reported by Rabidoux (2005) and used here are considered representative of those entering the lake, as all sampling sites were located at or near stream mouths where flow directly entered the lake.

Preliminary analysis of relations between flow discharge and particle concentration in *n*/ml undertaken in this study using the same dataset showed extremely low regression coefficients and flat regression slopes (Figure 7). An example of the regression for Blackwood Creek is shown in Figure 8 where a quadratic relation provided the best fit. The lack of significant relations between concentration of fine particles and flow is not surprising given that particles finer than sand, and particularly those finer than silt, are not hydraulically controlled. Thus, relations between particle flux and water discharge are almost akin to multiplying discharge by a constant particle concentration.

More meaningful relations for extrapolating annual particle flux (in *n*/year) were obtained by regressing total, suspended-sediment concentration (in mg/l), with particle concentration of the 5-20 μm fraction (in *n*/ml) analyzed using the Liquilaz instrument (Table 6). The improvement in r^2 values can be seen by comparing the values for the selected stations as shown in Table 7. That the slope of the regression lines is significantly greater than 0.0 also attests to the improved viability of the regressions. Example relations developed in log-log space for sites with particle flux data are shown in Figure 9. Regression of these two variables provides a functional link between the total mass of suspended-sediment transported at a given time and the number of particles in the 5-20 μm fraction.

COMBINED-STABILITY RANKING SCHEME

Station #_____ **Station Description**_____

Date _____ **Crew** _____ **Samples Taken**_____

Pictures (circle) U/S D/S X-section **Slope**_____ **Pattern:** Meandering Straight Braided

1. Primary bed material

Bedrock	Boulder/Cobble	Gravel	Sand	Silt Clay
0	1	2	3	4

_____

2. Bed/bank protection

Yes	No	(with)	1 bank protected	2 banks
0	1		2	3

_____

3. Degree of incision (Relative ele. Of "normal" low water; floodplain/terrace @ 100%)

0-10%	11-25%	26-50%	51-75%	76-100%
4	3	2	1	0

_____

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

0-10%	11-25%	26-50%	51-75%	76-100%
0	1	2	3	4

_____

5. Streambank erosion (Each bank)

	None	fluvial	mass wasting (failures)
Left	0	1	2
Right	0	1	2

_____
_____

6. Streambank instability (Percent of each bank failing)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

_____
_____

7. Established riparian woody-vegetative cover (Each bank)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	2	1.5	1	0.5	0
Right	2	1.5	1	0.5	0

_____
_____

8. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	2	1.5	1	0.5	0
Right	2	1.5	1	0.5	0

_____
_____

9. Stage of channel evolution

I	II	III	IV	V	VI
0	1	2	4	3	1.5

_____

10. Composition of adjacent side slope (circle)

	N/A	Bedrock	Boulders	Gravel-SP	Fines
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

_____
_____

11. Percent of slope (length) contributing sediment

	0-10%	11-25%	26-50%	51-75%	76-100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

_____
_____

12. Severity of side-slope erosion

	None	Low	Moderate	High
Left	0	0.5	1.5	2
Right	0	0.5	1.5	2

_____
_____

Total _____

FIGURE 4. Combined-Stability Index Field Form and Ranking Scheme.

To obtain estimates of annual, fine-particle (5-20 μm) flux, the relations shown in Figure 9 were applied to total, suspended-sediment load data for each of the stations over their daily-values period of record. Daily suspended-sediment load data were calculated for each of the index stations from mean-daily

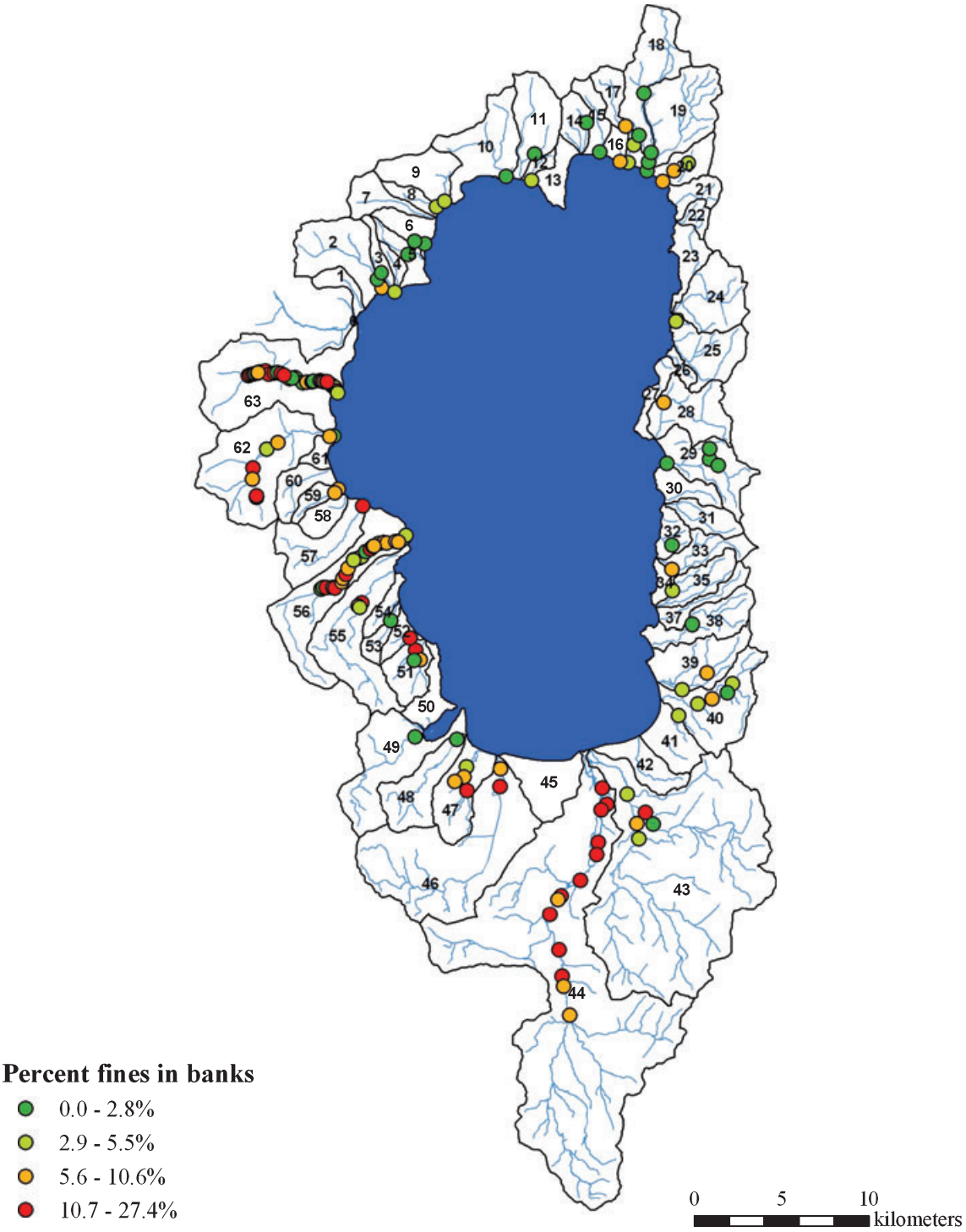

FIGURE 5. Spatial Distribution of Fine-Grained (<0.063 mm) Bank Materials.

flow data and the sediment-rating relations developed in Simon *et al.* (2003). These suspended-sediment transport ratings represent flow and concentration (or load) data collected over extended periods (up to 40 years) (Table 2). In a number of cases, the transport relations were not represented by a single linear segment (in log-log space) but were split into several segments to appropriately represent the relation between flow and load over the range of possible discharges (Figure 10). In addition, rating relations for a given site displayed shifts with time, requiring different relations to be used for different time periods. These were generally split into pre-1997 and post-1997, thus accounting for the effects of the large New

TABLE 4. Average, Combined-Stability Index for Streams Draining to Lake Tahoe.

Watershed (km^2)	Stream	Combined Stability-Index	Basin Area	Quadrant
39	Burke	10.0	12.8	E
32	Cave Rock	16.8	4.1	E
27	Dead Mans Point	13.5	3.5	E
40	**Edgewood**	17.8	17.2	E
29	**Glenbrook**	19.3	13.0	E
33	Lincoln	14.5	6.7	E
31	**Logan House**	12.9	5.6	E
38	McFaul	17.6	10.2	E
30	North Logan House	15.0	5.3	E
35	North Zephyr	16.3	6.8	E
	Skyland		2.0	E
28	Slaughterhouse	15.3	12.3	E
37	Zephyr	21.0	4.9	E
3	Barton	6.5	2.6	N
22	Bonpland	9.0	2.3	N
16	Burnt	16.3	2.3	N
2	Burton	9.1	14.8	N
8	Carnelian Bay	7.0	2.6	N
9	Carnelian Canyon	7.5	9.2	N
6	Cedar Flats	8.3	4.7	N
5	Dollar	6.5	4.7	N
	East Stateline Point		4.8	N
14	First	15.6	4.5	N
11	Griff	13.6	11.8	N
19	Incline	17.5	17.4	N
12	Kings Beach	14.5	1.6	N
4	Lake Forest	4.2	1.8	N
24	Marlette	21.8	11.3	N
20	Mill	17.3	12.4	N
	Sand Harbor		5.6	N
15	Second	19.1	4.8	N
25	Secret Harbour	12.2	11.1	N
1	Tahoe State Park	10.0	3.1	N
10	Tahoe Vista	11.4	15.5	N
18	**Third**	14.2	15.5	N
21	Tunnel	14.1	4.4	N
7	Watson	4.3	6.0	N
17	Wood	13.0	6.1	N
42	Bijou	11.7	7.3	S
41	Bijou Park	18.5	8.0	S
	Camp Richardson		10.1	S
48	Cascade	12.0	11.1	S
47	Tallac	8.4	11.9	S
46	Taylor	8.0	41.0	S
43	**Trout**	14.9	106.6	S
44	**Upper Truckee**	16.6	144.2	S
62	**Blackwood**	17.4	28.8	W
26	Bliss	14.0	1.6	W
50	Bliss State Park	5.5	5.4	W
49	**Eagle**	7.0	20.4	W
	Eagle Rock		2.1	W
45	**General**	16.1	23.3	W
59	Homewood	13.1	2.6	W
53	Lonely Gulch	8.3	2.8	W
60	Madden	9.3	5.9	W
57	McKinney	7.2	22.2	W
55	Meeks	13.0	5.7	W
52	Paradise Flat	18.0	2.9	W
58	Quail Lake	6.5	4.2	W
51	Rubicon	9.2	7.4	W
54	Sierra	6.0	3.1	W
63	**Ward**	13.9	34.2	W

Note: Values are based on criteria shown in Figure 4. Streams listed in **bold** contain historical data on suspended-sediment loads (Simon *et al.*, 2003).

TABLE 5. Distribution of Average, Combined Stability-Index by Basin Quadrant.

Combined Stability-Index Percentiles					
10th	25th	50th	75th	90th	Quadrant
13.0	14.3	15.8	17.6	19.1	E
6.5	7.9	12.2	15.1	17.5	N
8.2	10.0	12.0	15.7	17.4	S
6.2	7.1	9.3	13.9	16.9	W

Year's Day rainstorm in 1997 that created super-saturated snow packs and resulted in large runoff events in many parts of the Lake Tahoe Basin. A summary of the number and type of rating relations used to calculate daily, suspended-sediment loads from each of the index stations is shown in Table 8.

The number of fine particles (5-20 μm) transported on a given day was thus calculated for each day at each index station based on the equations in Figure 10 transposed to relations between fine-particle flux (in *n*/day) and suspended-sediment load (in T/day) (Table 9). This was done because the daily, sediment loadings datasets from Simon *et al.* (2003) were expressed in T/d. Summing the daily values for each year, provided an annual fine-particle flux for each year of record.

The procedure for extrapolating average, annual fine-particle flux yield data to ungaged watersheds was accomplished by first sorting the average, annual values (in *n*/year/km^2) by basin quadrant and determining the distribution within each quadrant. As done previously, distributions for each quadrant were defined in terms of the 10th, 25th, 50th, 75th, and 90th percentiles. For a given stream, the correct quadrant and appropriate percentile class was selected based on the combined-stability index distribution (Table 5). That same quadrant, percentile class was then selected from the average, annual flux yield distribution in Table 10. By multiplying that value by the basin area (in km^2) the average, annual particle flux of the 5-20 μm fraction (in *n*/year/km^2) was obtained.

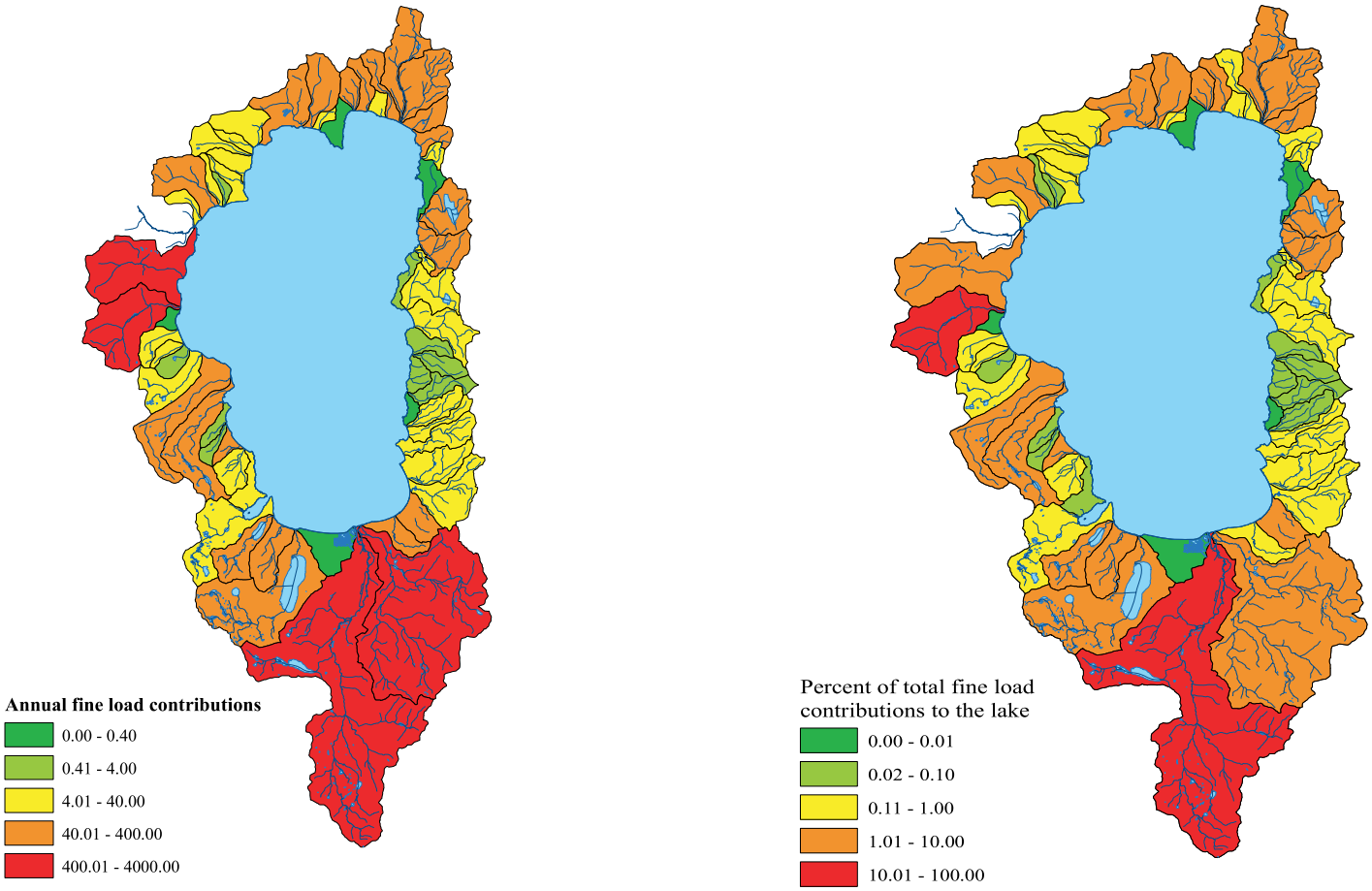

FIGURE 6. Median, Annual Contribution of Fine Sediment (<63 μm) in T/year (left), and Percent of Annual Contribution of Fine Suspended Sediment (<63 μm) to Lake Tahoe (right).

TABLE 6. Sampling Sites of Water-Sediment Mixtures by University of California, Davis Between 2002 and 2004 (Rabidoux, 2005).

Stream	USGS Station Number	Number of Samples
Blackwood Creek	10336660	71
Eagle Rock Creek	103367592	59
Edgewood Creek	10336760	62
General Creek	10336645	69
Glenwood Creek	10336730	59
Incline Creek[1]	10336700	73
Logan House Creek	10336740	59
Third Creek	10336698	72
Trout Creek[1]	10336790	65
Upper Truckee River[1]	10336610	72
Ward Creek	10336676	75

[1]Additional samples taken at other sites along stream.

A summary of the results, using the above procedure is shown in Table 11. On average, a total of 7.79E + 19 fine particles (<0.020 mm) are delivered to Lake Tahoe on an annual basis from the 63 contributing watersheds (excluding the intervening zones). The

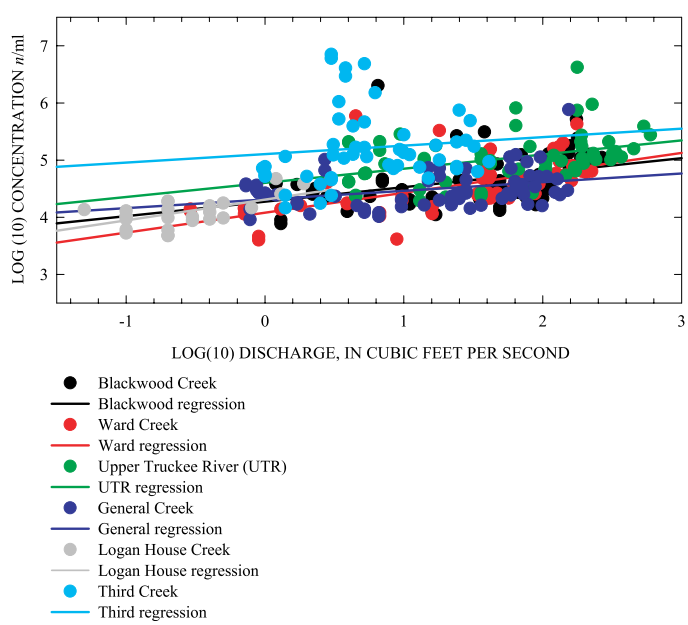

FIGURE 7. Example Linear Relations Between Concentration of Fine Particles (5-20 μm) and Discharge for Six Selected Streams (data from Rabidoux, 2005).

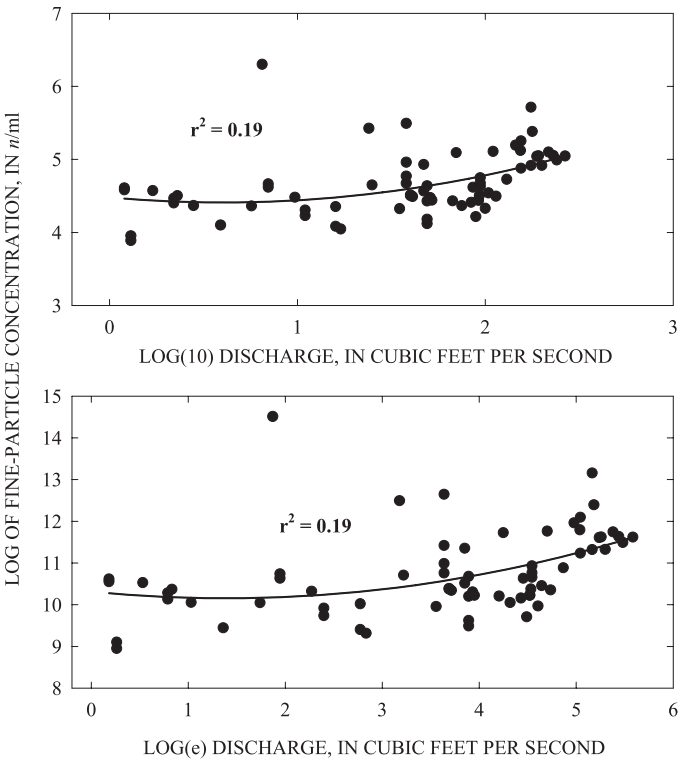

FIGURE 8. Example Quadratic Relations of Fine-Particle Concentration (5-20 μm) Regressed Against Discharge for Blackwood Creek Using Data From Rabidoux (2005) and Showing Very Low Coefficients of Determination Between Variables Using Log Base 10 (top) and Natural Log (bottom).

TABLE 7. Coefficients of Determination (r^2-values) and Regression Slopes for Relations Between Fine-Particle (5-20 μm) Concentration (F) and Discharge (Q), and Total Suspended-Sediment Concentration (C) for Selected Stations.

Stream	r^2	Slope of Regression
Particle Concentration (F) *vs.* Q		
Blackwood	0.16	0.25
Ward	0.35	0.35
Upper Truckee	0.14	0.25
General	0.13	0.15
Logan House	0.40	0.36
Third	0.01	0.15
Particle concentration (F) *vs.* C		
Blackwood	0.67	0.79
Ward	0.74	0.74
Upper Truckee	0.52	0.51
General	0.31	0.39
Logan House	0.62	0.55
Third	0.36	0.51

Note the improved relations for regressions of F with C.

three leading contributors are the Upper Truckee River (1.93 E + 19), Blackwood Creek (5.44 E + 18), and Ward Creek (4.56 E + 18). A summary of fine-particle flux for each stream is given in Simon *et al.*

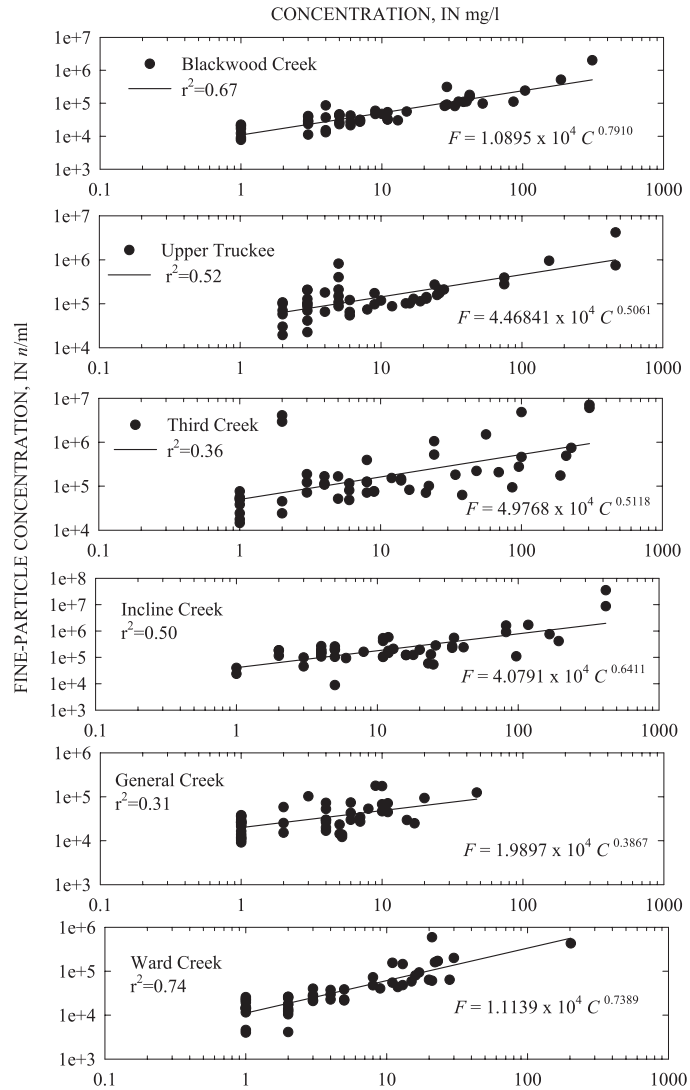

FIGURE 9. Example Regressions Between Fine-Particle (5-20 μm) Concentration (F) in n/ml and Total, Suspended-Sediment Concentration (C) in mg/l.

(2003). The spatial distribution of fine-particle flux in n/year and the relative contribution (in percent) from each watershed are displayed in Figure 11.

Estimates of Fine-Sediment Contributions From Streambank Erosion: <0.063 mm

Whereas estimates of fine-particle loadings and flux to Lake Tahoe relied on generating relations between total, suspended-sediment loadings and fine-particle loadings or flux from measured data at various index stations, estimates of fine-sediment contributions from streambank erosion presented a different challenge. In this case, the fine-particle loadings or flux measured at the index stations or

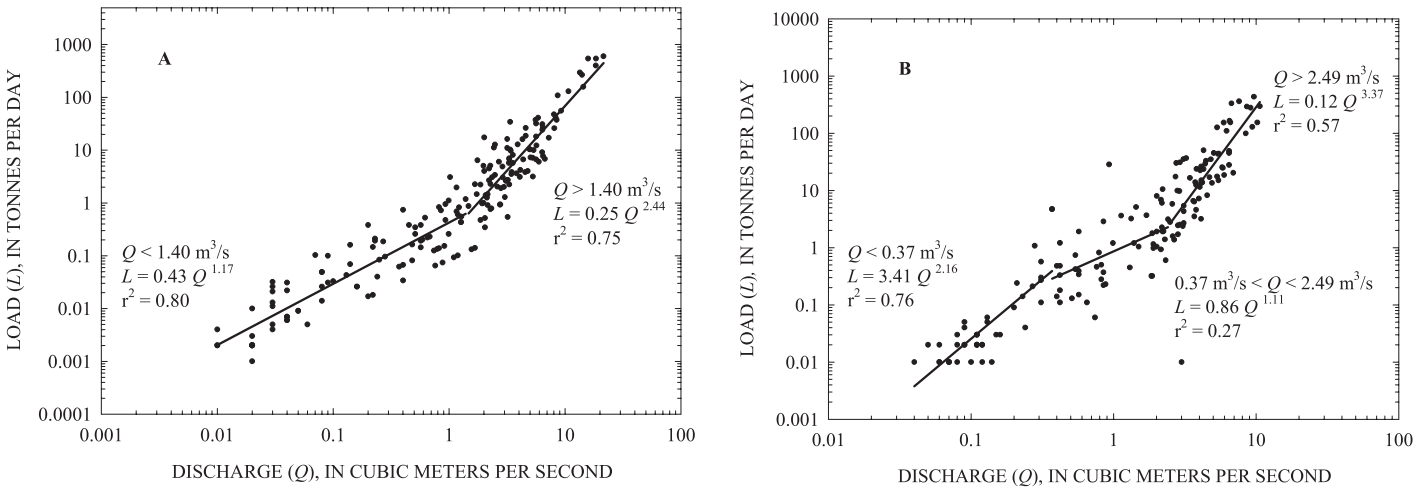

FIGURE 10. Example of Two-Segment and Three-Segment Suspended-Sediment Rating Relations for Blackwood Creek (A), and General Creek (B).

TABLE 8. Number and Type of Suspended-Sediment Rating Relations Used to Calculate Mean-Daily Suspended-Sediment Loads.

Stream	Station	Data Period: Flow	Data Period: Suspended Sediment	Pre-/Post-1997 Data Available?	Number of Rating Sections: Pre-1997	Number of Rating Sections: Post-1997
Blackwood	10336660	10/1/60-9/30/01	5/16/74-8/19/02	Y	3	3
Eagle Rock	103367592	11/18/89-9/30/00	11/2/89-9/13/02	Y	1	1
Edgewood	10336760	10/1/92-9/30/00	8/20/92-9/13/02	Y	1	1
General	10336645	7/7/80-9/30/01	4/30/81-9/19/02	Y	2	2
Glenbrook	10336730	10/1/71-9/30/00	10/18/71-9/13/02	Y	1	2
Incline	10336700	10/1/69-9/30/00	10/15/69-9/16/02	Y	1	1
Logan House	10336740	10/1/83-9/30/00	5/10/84-9/13/02	Y	2	2
Third	10336698	10/1/69-9/30/00	10/15/69-9/16/02	Y	1	1
Trout	10336790	10/1/71-9/30/92	3/4/72-9/11/02	Y	1	0
UTR	10336610	10/1/71-9/30/01	11/4/72-9/12/02	Y	1	1
Ward	10336676	10/1/72-9/30/01	12/20/72-9/19/02	Y	2	2

Note: Dates are mm/dd/yy notation.

TABLE 9. Regression Equations Between Fine-Particle Flux (in n/day) and Suspended-Sediment Load (in T/day) Used to Calculate the Daily and Annual Flux for Each Index Station.

Stream	Function	Basin Area (km^2)	Median Annual Flux (n/year)	Median Annual-Flux Yield (n/year/km^2)
Blackwood Creek (10336660)	$F = 5.1054 \times 10^{15} L^{0.8126}$	28.8	5.44E + 18	1.88E + 17
Eagle Rock Creek (103367592)	$F = 8.1701 \times 10^{15} L^{1.1836}$	1.53	1.74E + 16	1.14E + 16
Edgewood Creek (10336760)	$F = 7.1390 \times 10^{15} L^{0.6894}$	17.2	4.67E + 17	3.28E + 16
General Creek (10336645)	$F = 1.3679 \times 10^{15} L^{0.7499}$	23.3	2.05E + 17	1.06E + 16
Glenbrook Creek (10336730)	$F = 5.2060 \times 10^{15} L^{0.7632}$	13.0	1.03E + 17	9.81E + 15
Incline Creek (10336700)	$F = 9.0419 \times 10^{15} L^{0.6834}$	17.4	2.42E + 18	1.33E + 17
Logan House Creek (10336740)	$F = 1.4239 \times 10^{15} L^{0.8100}$	5.6	9.29E + 15	1.72E + 15
Third Creek (10336698)	$F = 7.6192 \times 10^{15} L^{0.6174}$	15.5	3.37E + 18	2.15E + 17
Trout Creek (10336790)	$F = 1.3358 \times 10^{15} L^{0.6310}$	106.6	4.18E + 18 (8.16E + 18)[1]	4.00E + 16 (8.59E + 16)
Upper Truckee River (10336610)	$F = 1.7579 \times 10^{16} L^{0.7141}$	144.2	1.93E + 19	1.36E + 17
Ward Creek (10336676)	$F = 6.6512 \times 10^{15} L^{0.9080}$	34.2	4.56E + 18	1.82E + 17

Note: F, fine-particle (0.5-20 μm) flux, in (n/day); L, suspended-sediment load in (T/day).

estimated by the previously discussed procedures represent fine-sediment loadings from all possible sources. This could include floodplains, slopes, channel beds and banks, and urban areas. In general, the technique to estimate basinwide fine-sediment contributions from streambank erosion relied on extra-

TABLE 10. Distribution of Average, Annual Flux Yields in n/year/km^2 by Basin Quadrant.

Percentiles of Average, Annual Flux Yield in n/year/km^2					
10th	**25th**	**50th**	**75th**	**90th**	**Quadrant**
3.34E + 15	5.77E + 15	9.81E + 15	2.13E + 16	2.82E + 16	E
1.41E + 17	1.54E + 17	1.74E + 17	1.95E + 17	2.07E + 17	N
4.92E + 16	6.30E + 16	8.59E + 16	1.11E + 17	1.26E + 17	S
4.49E + 16	9.63E + 16	1.82E + 17	1.85E + 17	1.87E + 17	W

polating rates of streambank erosion obtained from time-series measurements of monumented cross sections (Nolan and Hill, 1991) or from numerical simulations with the CONCEPTS channel-evolution model (Simon *et al.*, 2003).

Cross sections on Blackwood, General, Logan House, and Edgewood creeks were monumented with metal fence posts and labeled with brass plates (Hill *et al.*, 1990) by the USGS in 1983 and 1984. New surveys were conducted at as many of these sites as could be located during the fall of 2002 and summer of 2004. Time-series cross sections of the Upper Truckee River were originally surveyed in 1992 and resurveyed in 2002, thus providing a 10-year record of channel changes (C. Walck, 2003, written communication). A summary of the historical cross-section data is provided in Table 12.

For sites with measured cross sections, the change in cross-sectional area for a given time period was determined by overlaying time-series surveys and calculating the area between the plotted lines. The location of the bank toe was determined for the original and 2002 surveyed sections and used to discriminate between erosion or deposition from the bed and banks. Examples are shown in Figure 12. Values between adjacent cross sections were averaged and then multiplied by the reach length to obtain a volume in m^3. Results are expressed as a rate (in m^3/year) and as a yield (in m^3/year/km of channel length). The average percentage of fines determined from samples of bank material (in Simon *et al.*, 2003) was multiplied by the volume of material eroded from the channel banks to determine rates and yields of fine-grained materials delivered by streambank erosion. Because fines were not found in measurable quantities on streambeds, bed erosion was neglected as a contributor of fine sediments.

Data on contributions from streambank erosion were also available from a previous study, using the deterministic, channel-evolution model CONCEPTS to simulate channel erosion and deposition along General and Ward Creeks and the Upper Truckee River (Simon *et al.*, 2003). The CONCEPTS numerical model (Langendoen, 2000) was used to simulate channel-width adjustment by incorporating the fundamental physical processes responsible for bank retreat: (1) fluvial erosion of bank-toe material by flow and (2) bank mass failure due to gravity. Required input data such as geotechnical shear strength, bank-toe erodibility, and particle-size distribution of bank materials had been measured in the field. An example is shown in Figure 13.

Unit rates of streambank erosion were derived from the numerical simulations to provide a unit streambank erosion rate in the same units as those calculated from time-series cross section calculations. The following procedure was used:

1. Calculate the area eroded in each cross section.
2. Take the average eroded area between successive cross sections.
3. Multiply by the distance between the midpoint of successive cross sections.
4. Divide by the number of years of simulation to obtain a rate in m^3/year.
5. Divide by the total reach length to obtain a rate in m^3/year/km of channel.

Extrapolation of Measured and Simulated Streambank Erosion Rates

To obtain the rate of streambank erosion of fine sediment (<0.063 mm) from the measured and simulated unit erosion rates, values were multiplied by the average percentage of silt-clay in the channel banks, (in Simon *et al.*, 2003). Because validated simulation results for the Upper Truckee River extended almost the entire length of the alluvial section of this stream in comparison to the 2.9 km covered by the matched cross sections (Table 12), simulated erosion rates were used. The resulting rates of fine, streambank erosion are expressed in m^3/year/km and listed in Table 13.

To extrapolate this limited dataset to the entire Lake Tahoe Basin, diagnostic information obtained from the RGAs were used. Question 6 of the RGA field form (Figure 3) describing relative bank instability as the percentage (longitudinally) of each side of the channel that has experienced recent mass failure was used. This diagnostic criterion although simplistic,

TABLE 11. Summary of Annual Fine Load (<0.063 mm) and Annual Fine-Particle Flux (<0.020 mm) for Watersheds Draining to Lake Tahoe.

Watershed	Stream Name	Quadrant	Annual Fine Load (<63 μm) tonnes/year	% of Load (<63 μm)	% by Quadrant (<63 μm)	Annual Flux (0.5-20 μm) *n*/year	% of Load (0.5-20 μm)	% by Quadrant (0.5-20μm)
39	Burke	E	5.9	0.11		4.28E + 16	0.05	
32	Cave Rock	E	3.5	0.07		6.12E + 16	0.08	
27	Dead Mans Point	E	1.8	0.03		1.58E + 16	0.02	
40	**Edgewood**	E	**11.4**	0.22		**4.67E + 17**	0.60	
29	**Glenbrook**	E	**7.0**	0.13		**1.03E + 17**	0.13	
33	Lincoln	E	3.7	0.07		3.84E + 16	0.05	
31	**Logan House**	E	**2.3**	0.04		**9.29E + 15**	0.01	
38	McFaul	E	10.7	0.21		2.17E + 17	0.28	
30	North Logan House	E	3.3	0.06		4.12E + 16	0.05	
35	North Zephyr	E	4.7	0.09		6.65E + 16	0.09	
	Skyland	E	-	-		-	-	
28	Slaughterhouse	E	8.6	0.17		1.21E + 17	0.15	
37	Zephyr	E	6.1	0.12	1.3	1.37E + 17	0.18	1.7
3	Barton	N	4.9	0.09		3.70E + 17	0.48	
22	Bonpland	N	8.7	0.17		3.49E + 17	0.45	
16	Burnt	N	36.2	0.70		4.69E + 17	0.60	
2	Burton	N	79.9	1.53		2.43E + 18	3.12	
8	Carnelian Bay	N	7.8	0.15		1.16E + 17	0.15	
9	Carnelian Canyon	N	35.4	0.68		1.42E + 18	1.82	
6	Cedar Flats	N	18.0	0.35		7.23E + 17	0.93	
5	Dollar	N	8.8	0.17		6.62E + 17	0.85	
	East Stateline Point	N	-	-		-	-	
14	First	N	61.7	1.18		8.79E + 17	1.13	
11	Griff	N	121	2.33		2.16E + 18	2.78	
19	**Incline**	N	**129**	2.48		**1.63E + 18**	2.09	
12	Kings Beach	N	22.4	0.43		3.02E + 17	0.39	
4	Lake Forest	N	3.4	0.06		2.56E + 17	0.33	
24	Marlette	N	199.2	3.83		2.34E + 18	3.01	
20	Mill	N	218.8	4.20		2.57E + 18	3.30	
	Sand Harbor	N		0.00		-	-	
15	Second	N	84.0	1.61		9.89E + 17	1.27	
25	Secret Harbour	N	78.5	1.51		1.92E + 18	2.47	
1	Tahoe State Park	N	8.8	0.17		5.14E + 17	0.66	
10	Tahoe Vista	N	110	2.11		2.69E + 18	3.46	
18	**Third**	N	318	6.11		3.37E + 18	4.33	
21	Tunnel	N	44.2	0.85		8.13E + 17	1.04	
7	Watson	N	11.2	0.22		8.49E + 17	1.09	
17	Wood	N	43.5	0.83	31.8	1.07E + 18	1.37	37.1
42	Bijou	S	43.9	0.84		6.28E + 17	0.81	
41	Bijou Park	S	55.0	1.06		1.01E + 18	1.29	
	Camp Richardson	S	-	-		-	-	
48	Cascade	S	66.8	1.28		9.57E + 17	1.23	
47	Tallac	S	60.7	1.17		5.83E + 17	0.75	
46	Taylor	S	210	4.03		2.01E + 18	2.59	
43	**Trout**	S	**462**	8.87		**4.18E + 18**	5.37	
44	**Upper Truckee**	S	**1010**	19.40	36.6	**1.93E + 19**	24.8	36.8
62	**Blackwood**	W	**846**	16.25		**5.44E + 18**	6.98	
26	Bliss	W	20.8	0.40		2.96E + 17	0.38	
50	Bliss State Park	W	4.4	0.08		2.43E + 17	0.31	
49	**Eagle**	W	**21.8**	0.42		1.96E + 18	2.52	
	Eagle Rock	W	-	-		-	-	
45	**General**	W	**53.3**	1.02		**2.05E + 17**	0.26	
59	Homewood	W	33.9	0.65		4.83E + 17	0.62	
53	Lonely Gulch	W	3.9	0.08		3.92E + 16	0.05	
60	Madden	W	11.4	0.22		1.07E + 18	1.37	
57	McKinney	W	20.2	0.39		2.14E + 18	2.74	
55	Meeks	W	73.8	1.42		2.55E + 17	0.33	
52	Paradise Flat	W	54.3	1.04		5.35E + 17	0.69	
58	Quail Lake	W	3.4	0.06		2.93E + 17	0.38	

TABLE 11. Continued. Summary of Annual Fine Load (<0.063 mm) and Annual Fine-Particle Flux (<0.020 mm) for Watersheds Draining to Lake Tahoe.

Watershed	Stream Name	Quadrant	Annual Fine Load (<63 μm) tonnes/year	% of Load (<63 μm)	% by Quadrant (<63 μm)	Annual Flux (0.5-20 μm) *n*/year	% of Load (0.5-20 μm)	% by Quadrant (0.5-20μm)
51	Rubicon	W	14.3	0.27		1.35E + 18	1.73	
54	Sierra	W	2.5	0.05		1.38E + 17	0.18	
63	**Ward**	W	**412**	7.91	30.3	**4.56E + 18**	5.85	24.4
	Total		5206	100		7.79E + 19	100	100

Note: Sites in bold represent index stations.

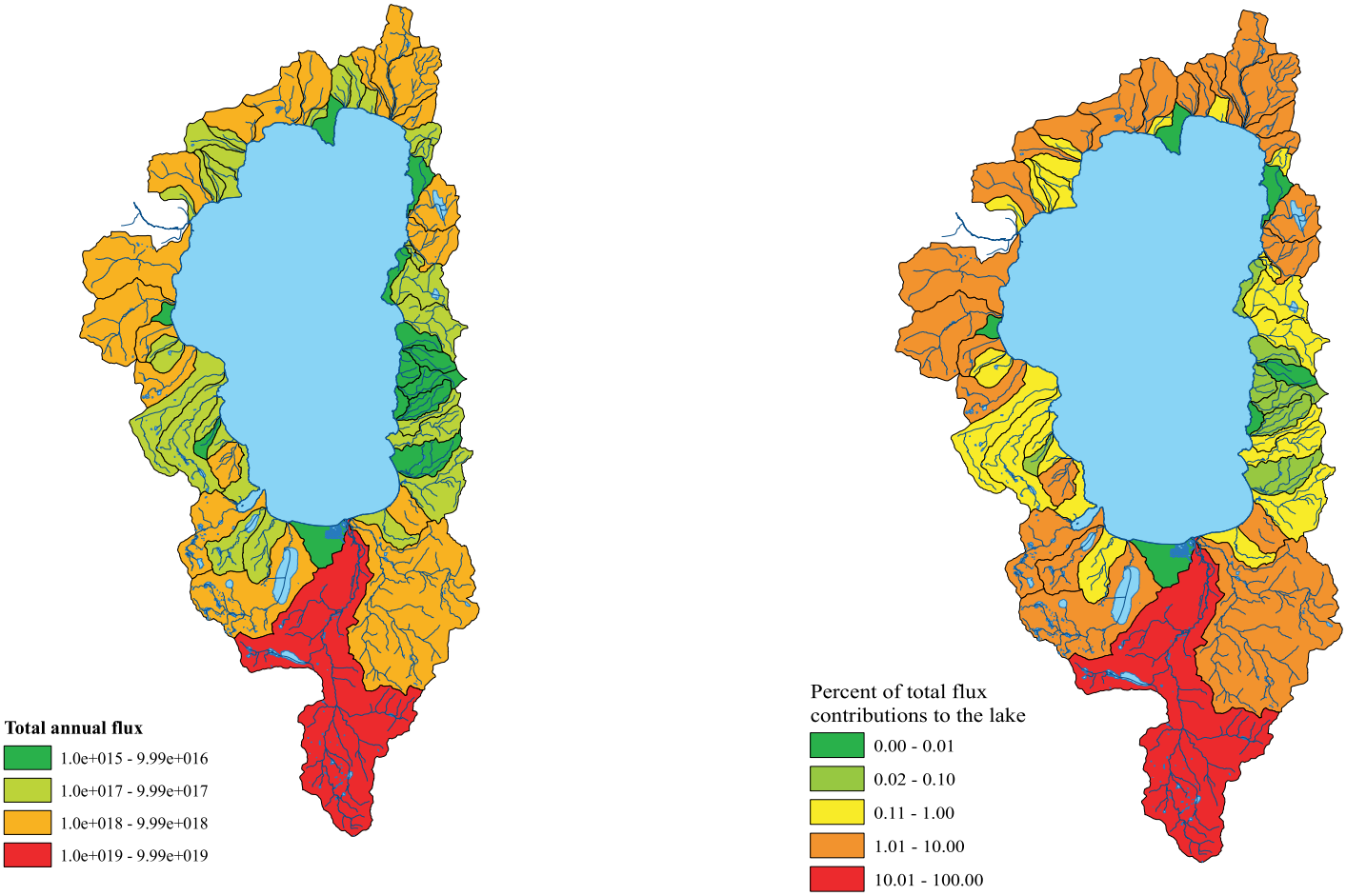

FIGURE 11. Median Annual Fine-Particle Flux (0.5-20 μm) to Lake Tahoe, in *n*/year (left), and Percent Contribution of Annual Fine-Particle Flux (0.5-20 μm) to Lake Tahoe (right).

TABLE 12. Summary of Historical Cross-Sectional Data Available for This Study.

Stream	Date of First Survey	Number of Sections Matched	Total Matched Length (km)	Percentage of Total Length	Source of Historical Data
Blackwood	1983	17	8.3	83	USGS[1]
Edgewood	1983	23	5.6	63	USGS[1]
General	1983	12	8.5	57	USGS[1]
Logan House	1984	10	3.3	62	USGS[1]
Upper Truckee	1992	24	2.9	8	Calif. Parks[2]

[1]Data from K.M. Nolan (2003, written communication).
[2]Data from C.M. Walck (2003, written communication).

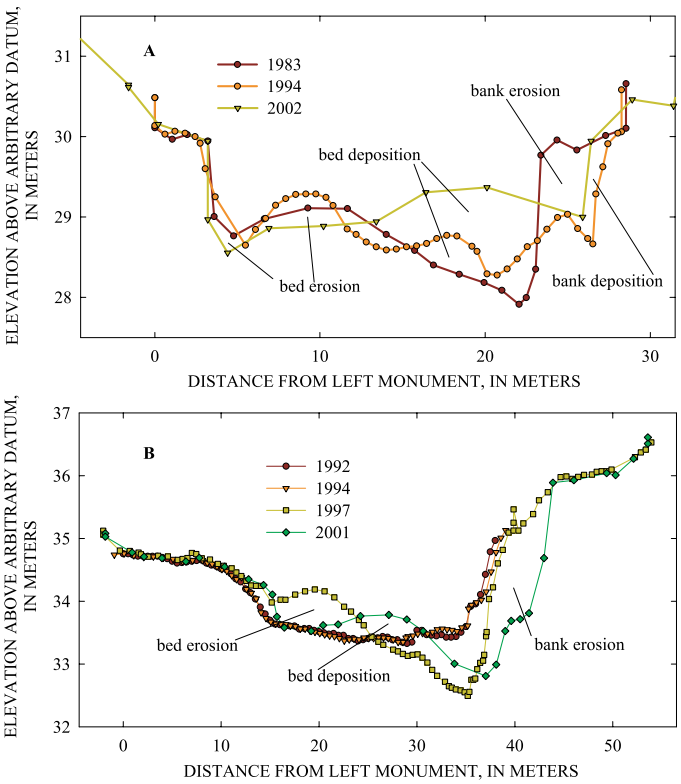

FIGURE 12. Examples of Overlain Surveys From Blackwood Creek (A) and the Upper Truckee River (B).

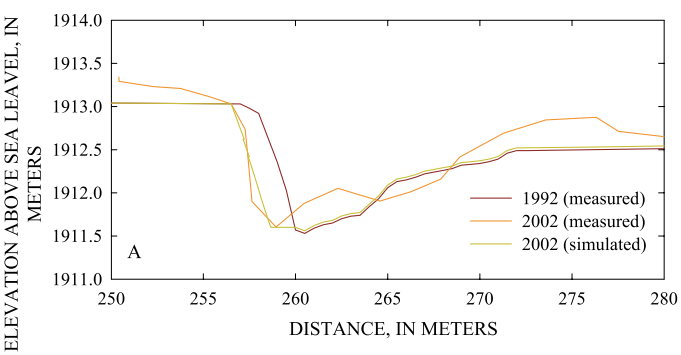

FIGURE 13. Example Comparison of Simulated and Measured Streambank Erosion Between 1992 and 2002 Along the Upper Truckee River. Modified from Simon *et al.* (2003).

synthesizes the effects of quantitative variables such as bank strength, bank-toe erodibility and the reinforcing effects of vegetation. Observed conditions ranged from 0 (stable banks) to 100%, where the entire reach contained failing streambanks. An example from Blackwood Creek shows the average, longitudinal extent of bank failures evaluated at 17 sites along the creek (Figure 14). Each bank was assigned a numerical value, termed the bank-stability index (I_B) based on the extent of failures (Table 14). The index attempts to synthesize more quantitative evaluations of streambank stability that might include parameters such as bank height, bank angle, geotechnical strength, and bank-toe erodibility. An un-weighted, average I_B values (sum of all values divided by number of sites) was then calculated for each stream.

With an average bank-stability index (I_B) calculated for each stream from observed conditions, a relation between this parameter and measured streambank erosion rates was required for extrapolation to streams without measured data. Using data from the six streams with measured or simulated data (Table 12), a type of regression that best fit the general shape of the relation was used. This was a sigmoidal three-parameter equation that takes the general form (Figure 15)

$$y = \frac{a}{1 + e^{-\frac{(x - x_0)}{b}}}, \tag{2}$$

where a, b and x_0 are coefficients determined by regression. Regression yields the following relation (r^2 = 0.99):

$$E_r = \frac{12.6939}{1 + e^{-\frac{(I_B - 1.0217)}{0.1129}}}, \tag{3}$$

where E_r is erosion rate of fine (<0.063 mm) bank sediment in m^3/year/km of channel and I_B is average bank-stability index (percent of reach length with failing banks).

TABLE 13. Measured and Simulated Average, Annual Rates of Streambank Erosion.

Stream	Bank Composition (% finer 0.063 mm)	Erosion Rate (m^3/year/km)	Type of Data	Source of Data
Blackwood Creek	5.6	12.2	Measured	Simon *et al.*, 2003
Edgewood Creek	4.9	0.09	Measured	Nolan and Hill, 1991
General Creek	7.4	0.92	Simulated	Simon *et al.*, 2003
Logan House Creek	-	0.002	Measured	Nolan and Hill, 1991
Upper Truckee River	9.5	9.50	Simulated	Simon *et al.*, 2003
Ward Creek	10.4	4.40	Simulated	Simon *et al.*, 2003

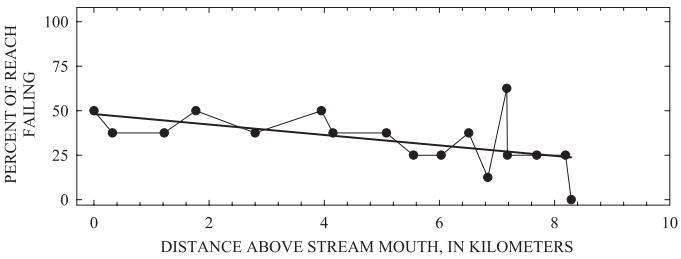

FIGURE 14. Observations of the Extent of Streambank Instability Along Blackwood Creek. Sloping line represents a trend of decreasing bank instability with distance upstream.

TABLE 14. Assigned Values for the Bank-Stability Index (I_B) Based on the Percent of Reach Length With Failing Banks.

Criteria					
Percent of reach with failing banks[1]	0-10%	11-25%	26-50%	51-75%	76-100%
Assigned index value[1]	0	0.5	1.0	1.5	2.0

[1]Evaluations and calculations are done for each bank and summed to obtain a value for the reach. A maximum value of 4.0, therefore, is possible for a reach.

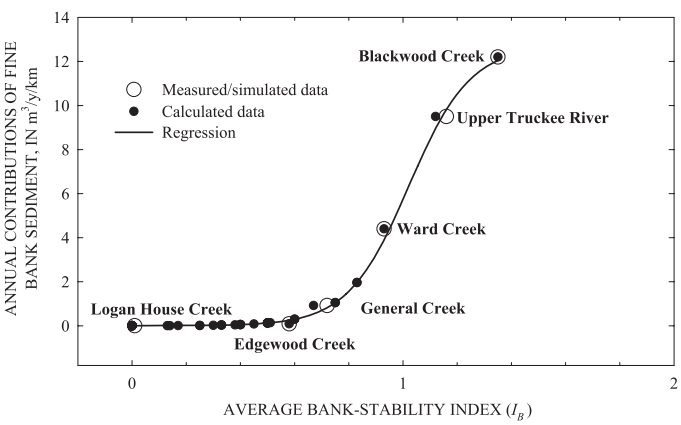

FIGURE 15. Relationship Between Average, Annual Streambank Erosion Rates, and Average Bank-Stability Index (I_B). Regression is a three-parameter sigmoidal equation; $r^2 = 0.99$.

An erosion rate for each stream was obtained by substituting the stream's value into the above regression equation (Equation 3) to provide an average, annual erosion rate of fine (<0.063 mm) sediment per unit length of channel expressed in m^3/year/km. Blackwood Creek manifests the highest streambank erosion rates per unit length of channel (12.2 m^3/year/km) followed by the Upper Truckee River (9.5 m^3/year/km) and Ward Creek (4.4 m^3/year/km), respectively. Results are shown in Figure 16 (left).

The average, annual volume (in m^3) of streambank erosion for each stream was then determined by multiplying the unit streambank erosion rate by the total length of main channels as calculated by Jorgensen *et al.* (1978). Modifications were made to some of these reported lengths based on observed tributary contributions and contributing lengths that were reduced because of dams. The volume of fine sediment (<0.063 mm) eroded from streambanks was converted to kilonewtons by multiplying by the average bulk unit weight of previously collected bank sediments (17.3 kN/m^3; standard deviation = 1.15 kN/m^3; standard error = 0.12 kN/m^3), and then to metric tonnes (T).

Using the above procedures, average, annual erosion, and delivery of fine sediment to Lake Tahoe were calculated for each stream. Resulting values are mapped in Figure 16 (right). Summing the values calculated for each of the 63 watersheds gives an annual, average of 1,305 T/year of fine (<0.063 mm) sediment delivered to Lake Tahoe from streambank erosion. From what has been learned in this and previous studies, it is no surprise that the three largest contributors of fine, streambank sediment are the Upper Truckee River (639 T/year), Blackwood Creek (431 T/year), and Ward Creek (104 T/year) (Figure 17).

About 25% of the fine sediment delivered to the lake from watershed outlets emanates from streambank erosion when compared to the total fine-loadings calculated in this report (5,206 T/year). In fact, about 20% of all fine sediment delivered to Lake Tahoe comes from the banks of the Upper Truckee River and Blackwood Creek. If Ward Creek is included, this value becomes 22%. This is shown most clearly in Figure 17B and helps to provide a rationale for agencies to focus bank-stabilization efforts in these watersheds.

The relative importance of fine-sediment erosion from streambanks was calculated by comparing average, annual loadings of fine, streambank sediment to total, fine sediment from all sources for the nine watersheds where fine loads had been calculated from measured data in Simon *et al.* (2003). For these streams, values range from 63% for the Upper Truckee River to 2.4% for Trout Creek (Table 14). It is interesting that the maximum and minimum values occur in adjacent watersheds within the same basin quadrant (South), indicating that anthropogenic disturbances to the channels of the Upper Truckee River have played an important role in destabilizing streambanks and creating conditions, where streambanks have become the dominant source of fine sediment. The relatively low value for Third Creek (10%) suggests that the dominant sources of fine sediments in this basin are probably the steep, bare upland slopes, and urbanized areas. The low percentage for Incline Creek (3.6%) is probably attributable to greater contributions from urban areas compared to streambanks.

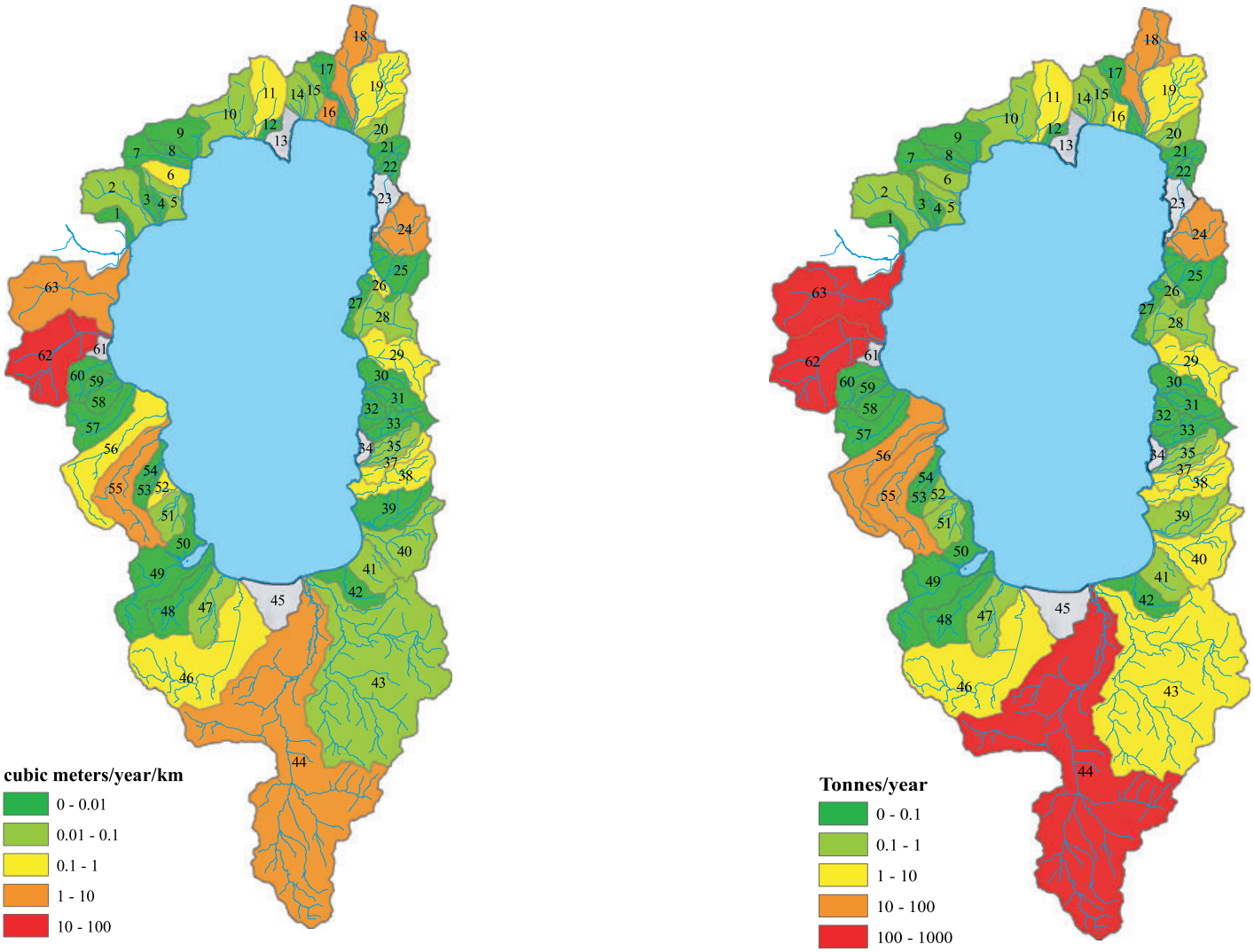

FIGURE 16. Unit Volume of Fine-Sediment (<0.063 mm) Contributions From Streambank Erosion Per Kilometer of Main Channels (left), and Loadings of Fine Sediment (<0.063 mm) From Streambank Erosion (right). Gray shading indicates no data available. See Figure 1 for watershed names.

A broader comparison of the relative importance of streambank erosion compared to all other sources of fine sediment in each of the 63 basins was made by comparing fine-sediment loadings estimates from all sources (Table 15 and Figure 6) with those solely from streambanks (Figure 16). Results are shown spatially (Figure 18), providing a means for action agencies to focus bank-stabilization efforts along streams with actively eroding banks.

SUMMARY AND CONCLUSIONS

The delivery of fine-grained sediment from tributary basins is listed as a major cause of water-clarity deterioration in Lake Tahoe. Efforts to control the discharge of fine sediment to the lake require knowledge of the volumes, rates, and sources of this material. Similarly, use of a lake-clarity model to predict future clarity conditions and the effectiveness of management alternatives also require these types of data. The research described in this report used combinations of field-based observations of channel and bank stability with measured and simulated data on fine-sediment loadings to estimate fine-sediment loadings from unmonitored basins throughout the Lake Tahoe Basin. Loadings were expressed in the conventional format of mass per unit time (T/year) but also in the number of particles finer than 20 μm, the latter for use in a lake-clarity model operated by the University of California, Davis.

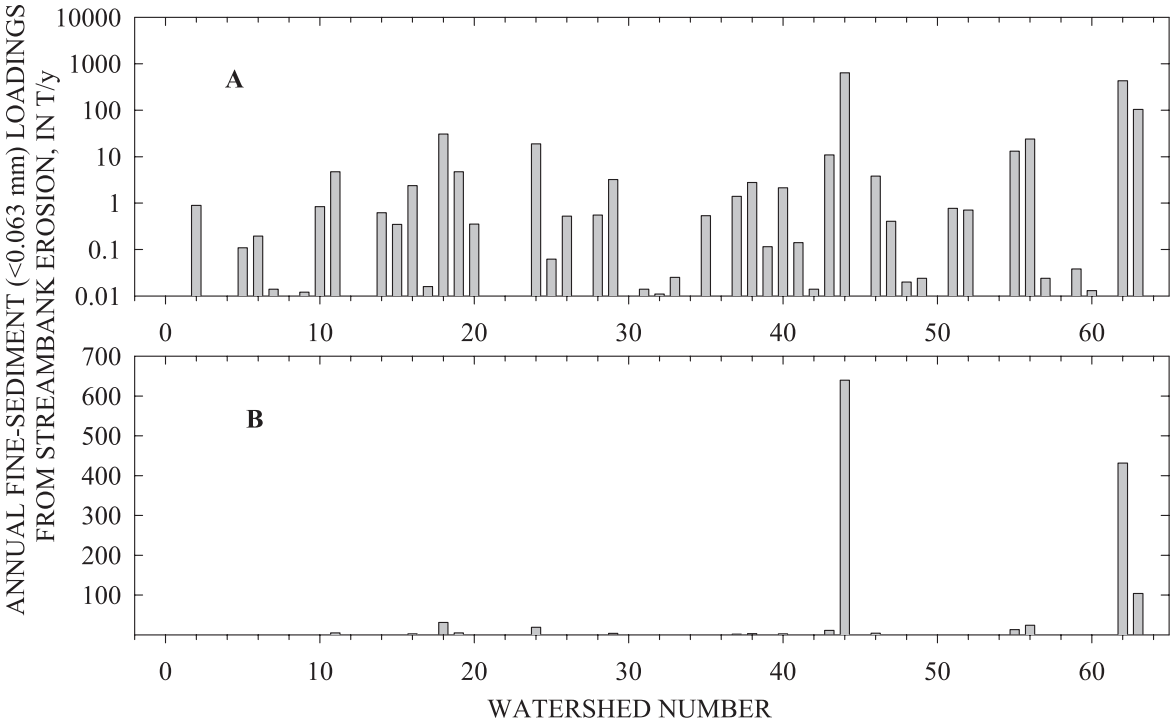

FIGURE 17. Annual, Fine-Sediment (0.063 mm) Loadings in Tonnes Per Year From Streambank Erosion Plotted With $\log_{10}$ Scale (A) and Arithmetic Scale (B). Note the relatively large contributions from the Upper Truckee River (#44), Blackwood Creek (#62), and Ward Creek (#63). See Figure 1 for watershed numbers.

TABLE 15. Comparison Between Measured, Median Annual Fine-Sediment (<0.063 mm) Loadings (from Simon *et al.*, 2003) and Estimated, Fine-Grained (<0.063 mm) Loadings From Streambanks.

Stream	Watershed Number	Fine Load, All Sources (T/year)	Fine Load, Streambanks (T/year)	Fine-Grained Contribution From Streambanks (%)
Upper Truckee River	44	1010	639	63
Blackwood Creek	62	846	431	51
Ward Creek	63	412	104	25
Third Creek	18	318	30.8	10
General Creek	56	53	23.9	45
Trout Creek	43	462	10.9	2.4
Incline Creek	19	129	4.7	3.6
Glenbrook Creek	29	7.0	3.2	46
Edgewood Creek	40	11.4	2.1	18

Three types of fine-sediment loadings estimates have been provided for the contributing watersheds: (1) average, annual fine-sediment (<0.063 mm) loadings in T/year; (2) average, annual fine-sediment (<0.020 mm) loadings in *n*/y; and (3) average, annual fine-sediment (<0.063 mm) loadings in T/year from streambank erosion.

Fine-sediment (<0.063) loadings in T/year for each un-monitored watershed were based on extrapolating relations between distributions of a combined-stability index and measured fine yields (T/year/km^2) within each basin quadrant. The greatest contributors happened to be those with measured data, not requiring extrapolation. In descending order they are as follows: Upper Truckee River (1,010 T/year), Blackwood Creek (846 T/year), Trout Creek (462 T/year), and Ward Creek (412 T/year). Summing the values from the contributing watersheds provided an average, annual estimate of fine-sediment (<0.063 mm) loadings to the lake of 5,206 T/year. Fine-sediment loadings to the lake could, however, be greater because contributions from the five intervening zones are not included in the analysis.

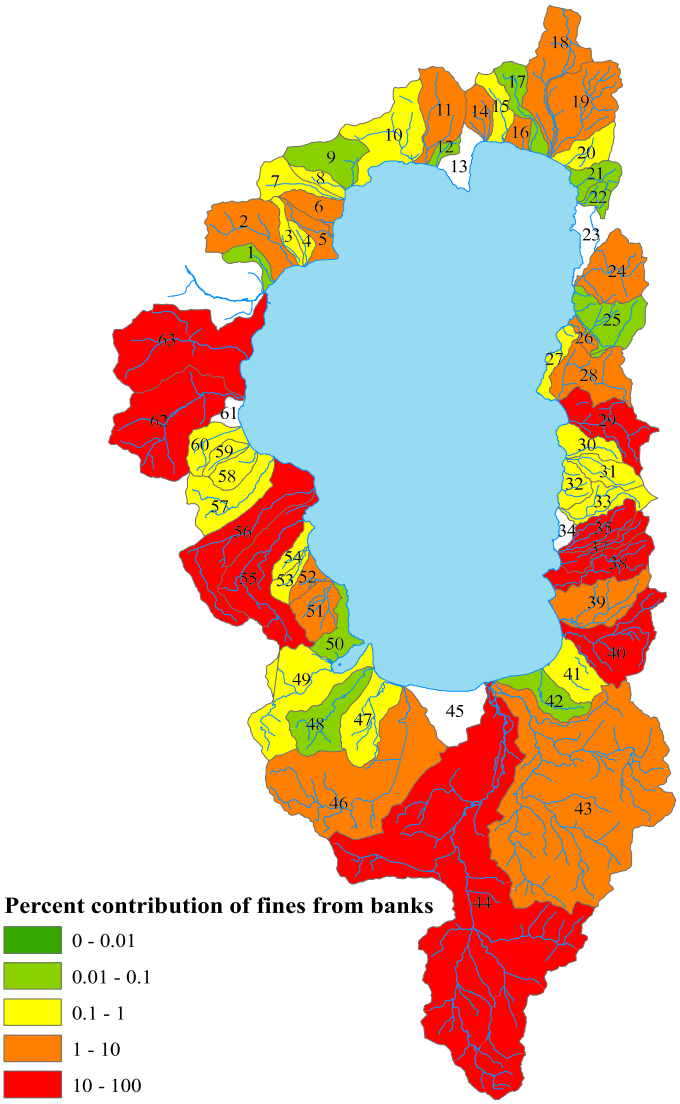

FIGURE 18. Contribution of Fine (<0.063 mm) Sediment From Streambanks Compared to All Other Sources Within a Given Watershed. See Figure 1 for watershed names.

Fine-sediment (<0.063 mm) loadings in T/year had to be converted to loadings expressed as the number of particles per year finer than 0.020 mm for use in the lake-clarity model. This was accomplished using data from Rabidoux (2005) by establishing relations between total suspended-sediment concentration (in mg/l) and the concentration of the 5-20 μm fraction in number per milliliter. Resulting data were converted to mean-daily and then annual values using suspended-sediment rating relations from Simon *et al.* (2003). A total of 7.79E + 19 particles in the 5-20 μm fraction were calculated to enter Lake Tahoe in an average year with the Upper Truckee River accounting for almost 25% of the total. Contributions from Blackwood, Ward, Trout, and Third creeks account for another 23% of these very fine particles. Thus, these five streams making up about 40% of the basin area, account for almost 50% of all fine-sediment loadings to the lake.

Contributions of fine sediment from streambank erosion were estimated by developing empirical relations between measured or simulated bank-erosion rates (adjusted for the content of silt and clay in the bank material) with a field-based measure of the extent of bank instability along given reaches and streams. Measured, unit values of fine sediment (<0.063 mm) erosion rates ranged from 12.2 m^3/year/km for Blackwood Creek to 0.002 m^3/year/km for Logan House Creek. Multiplying by the length of main channels in the watershed produced estimates of fine-sediment streambank erosion for each of the watersheds in T/year. Summing the values for 57 contributing watersheds provided an average, annual fine-sediment loading from streambank erosion of 1,305 T/y. This represents about 25% of the average, annual fine-sediment load delivered to the lake from all sources. The two largest contributors, the Upper Truckee River (639 T/year) and Blackwood Creek (431 T/year), account for slightly more than 80% of all fines emanating from streambanks, representing about 20% of fine sediment delivered to Lake Tahoe from all sources.

Extrapolations of fine-sediment loadings to the un-monitored watersheds are based on documented empirical relations, yet contain a significant amount of uncertainty. Except for those values derived directly from measured data, reported results should be considered as estimates. Results are based on all of the data available at the time of writing and represent the best available science given the resources to conduct this work. In addition, loadings information from intervening zones and from shoreline erosion was not considered. Results also represent a significant increase in our understanding of the relative contribution of fine sediment from stream-channel erosion as opposed to other sources.

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