# SUSPENDED-SEDIMENT BUDGETS FOR FOUR DRAINAGE BASINS TRIBUTARY TO LAKE TAHOE, CALIFORNIA AND NEVADA, 1984-87

*By* K. Michael Nolan *and* Barry R. Hill

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4054

Prepared in cooperation with the
TAHOE REGIONAL PLANNING AGENCY

7219-15

Sacramento, California
1991

**U.S. DEPARTMENT OF THE INTERIOR**
**MANUEL LUJAN, JR.,** ***Secretary***

**U.S. GEOLOGICAL SURVEY**
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## Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| cubic meter ($m^3$) | 35.31 | cubic foot |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second |
| hectare | 2.471 | acre |
| kilometer (km) | 0.621 | mile |
| megagram (Mg) | 1.102 | ton, short |
| megagram per annum (Mg/a) | 1.102 | ton per year |
| megagram per day (Mg/d) | 1.102 | ton per day |
| megagram per kilometer per annum [(Mg/km)/a] | 1.77 | ton per mile per year |
| megagram per square kilometer ($Mg/km^2$) | 2.86 | ton per square mile |
| megagram per square kilometer per annum [($Mg/km^2$)/a] | 2.86 | ton per square mile per year |
| megagram per cubic meter ($Mg/m^3$) | 0.031 | ton per cubic foot |
| meter (m) | 3.281 | foot |
| meter per annum (m/a) | 3.281 | foot per year |
| millimeter (mm) | 0.03937 | inch |
| millimeter per hour (mm/h) | 0.03937 | inch per hour |
| square kilometer ($km^2$) | 0.3861 | square mile |
| square meter ($m^2$) | 10.76 | square foot |
| square meter per kilometer ($m^2/km$) | 17.3 | square foot per mile |

Temperature is given in degree Celsius (°C), which can be converted to degree Fahrenheit (°F) by the following equation:

Temp °F = 1.8 temp °C + 32.

## Vertical Datum

*Sea level*: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

## Definition

*Water year*: A water year is a 12-month period, October 1 through September 30, designated by the calendar year in which it ends. In this report, years are water years unless otherwise noted.

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## Abstract

Effective management of lands surrounding Lake Tahoe requires an understanding of processes controlling sediment delivery to the lake from tributary streams. Erosional processes were monitored along four Lake Tahoe tributary basins during 1984-87, and sediment budgets were formulated to identify processes that supply sediment to tributary streams. Data collection was adequate to describe the processes most important in the mobilization, transport, and storage of sediment in three of the four study basins. In the fourth basin, Logan House Creek, measured sediment output did not compare favorably with sediment output predicted by the sediment budget. Erosional processes in Logan House Creek apparently are operating too slowly to be adequately quantified in a 4-year study. Channel erosion mobilized more than 95 percent of the sediment in study basins with balanced sediment budgets. Average annual sediment yields from the study basins ranged from 0.7 to 67.9 megagrams per square kilometer. Differences in the processes and rates of channel erosion and in the sources of sediment within channel systems seem to be controlled by differences in precipitation, geology, basin physiography, and, to an unknown degree, land use. Because alluvial channels are the dominant source of mobilized sediment in the study basin, land-use changes virtually anywhere in a basin could affect sediment yields in that basin.

## INTRODUCTION

The pristine beauty and remarkable water clarity of Lake Tahoe in the Sierra Nevada of California and Nevada (fig. 1) have attracted attention for many years. However, an increase in algal production in the lake over the last several decades has caused a noticeable decrease in water clarity (Goldman and Byron, 1986). This increased algal production has been linked to increased nutrient loading by streams tributary to the lake (Goldman and Byron, 1986). A large proportion of nutrients delivered annually by streams consists of forms that are adsorbed to suspended sediment (Leonard and others, 1979). The protection of water quality in the lake therefore depends, in part, on controlling the discharge of suspended sediment to the lake by tributary streams. Large variations in sediment discharge have been observed among streams for which sediment records are available, but little is known concerning the processes that control the supply of sediment to these tributaries. Effective management of lands in the Lake Tahoe basin to improve lake water quality requires an understanding of these processes and their relative importance within tributary drainage basins.

The U.S. Geological Survey, in cooperation with the Tahoe Regional Planning Agency, conducted a study from 1984-87 to obtain data on sources, characteristics, volume, and rates of production and transport of eroded material in the Lake Tahoe basin in order to improve the understanding of the processes of erosion and deposition in the basin.

### PURPOSE AND SCOPE

This report describes the natural processes that control sediment discharge from the Blackwood Creek, General Creek, Edgewood Creek, and Logan House Creek drainage basins (fig. 1) to Lake Tahoe. This is done by presenting sediment budgets, which are quantitative assessments of the rate of sediment production, transport, and storage, for each of the four basins. Sediment budgets presented for 1984-87 are based on erosion and sediment-discharge data collected during years 1983-88. The four basins selected for study were chosen to represent the general variability in basin physiography, bedrock geology, vegetation, and hydrology found in the Lake Tahoe basin. Because the study was designed to address natural variations in sediment yield, land use was not a key element in selecting the study basins.

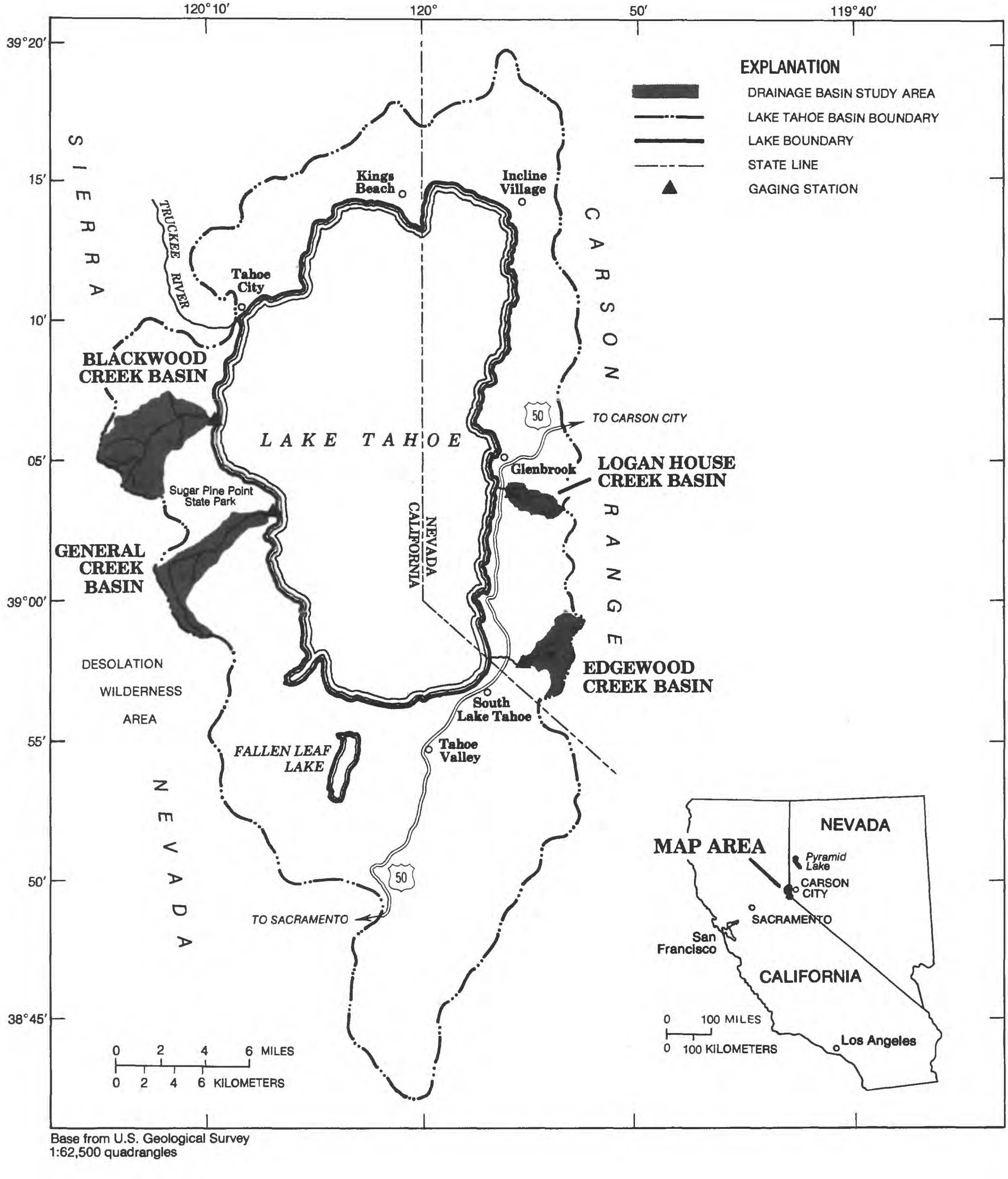

**Figure 1.** Location of study basins tributary to Lake Tahoe.

This report discusses data collected to assess rates of hillslope erosion, streambank erosion, streambed scour and fill, and amount of sediment storage in stream channels in each of the four study basins. Initial field reconnaissance of the physical characteristics of the Lake Tahoe basin indicated that stream-channel erosion and hillslope erosion by sheetwash, ravelling, rilling, and gullying are the major erosional processes in the basin. These processes were, therefore, the focus of the study. Although gully volumes were measured in the Blackwood and Edgewood Creek basins, gully volumes are not included in sediment budgets because the time frame over which measured gullies developed has not been defined. Most basic data have been presented in a report by Hill and others (1990). The present report includes only those data not previously published; when needed, previously published data are summarized.

## APPROACH

Erosional processes in the Lake Tahoe basin were studied by developing sediment budgets for four tributary drainage basins for a 4-year period, 1984-87. Sediment budgets were not developed for 1988 because only a limited amount of data was collected in 1988.

### SEDIMENT-BUDGET CONCEPT

Lehre (1981) defined a sediment budget of a basin as "a quantitative statement of relations between sediment mobilization and discharge, and of associated changes in storage." There are three requirements for the construction of a sediment budget: (1) recognition and quantification of transport processes (streambank erosion, streambed erosion, and hillslope erosion), (2) recognition and quantification of storage elements (streambed storage and colluvial storage), and (3) identification of linkages among transport processes and storage elements (Dietrich and others, 1982, p. 6). A common approach is to compare measured sediment output from a drainage basin with measurements of sediment-transport processes and storage changes within the basin (Lehre, 1981). Ideally, sediment input plus or minus sediment storage equals sediment output.

Except for very small basins, the variety and widespread distribution of sediment sources and sediment-deposition sites make it impossible to directly quantify rates at which all sediment-related processes operate. In basins larger than a few hectares in size, it is generally impossible to measure erosion and deposition along all channels or erosion from all hillslopes. Because of the need to generalize rates and types of erosional processes in unsampled areas of a basin, nearly all sediment budgets should be considered estimates. Development of sediment budgets requires merging available data with carefully derived conceptual models of erosion and sediment transport in a given basin. Investigators have used a variety of methods to accomplish this. For example, Kelsey (1980) produced a sediment budget for the 575 $km^2$ Van Duzen River basin in California by augmenting a limited amount of process monitoring with aerial-photograph interpretation, dating of alluvial deposits, and gaging-station records.

Many sediment budgets published to date were for areas where most of the stream sediment is supplied by landsliding (Kelsey, 1980; Lehre, 1981). In such areas, sediment is commonly delivered in discrete volumes that can be measured in the field or from aerial photographs. Few sediment-budget studies have quantified deposition or erosion from stream channels. Such components of sediment budgets are often estimated as a residual term. Not only do such residual terms include estimates for unmeasured elements of sediment budgets, they also incorporate any errors associated with the measured budget terms. Residual terms can be a significant component of sediment budgets. The residual term, channel storage, used by Lehre (1981), accounted for 44, 60, and 84 percent of the total sediment delivered to the channel during his 3-year study.

Quantification of channel erosion and deposition requires monitoring channel cross-section changes at a variety of sites over a period of years. It also requires some mechanism for extrapolating measured data to the length of all channels within a basin. Most sediment-budget studies rely on channel characteristics available from topographic maps to generalize cross-sectional data to entire basins. For example, Lehre and others (1983) used an approximate relation between cross-sectional change and stream order to estimate volume change along the North Fork Toutle River following the 1980 eruption of Mount St. Helens.

### APPLICATION OF SEDIMENT-BUDGET CONCEPTS TO LAKE TAHOE TRIBUTARIES

Field inspection of the Lake Tahoe study basins prior to collection of data for this study indicated that landsliding was not a particularly active erosional process. This means that dispersed processes like channel erosion, rainsplash, and sheetwash erosion on hillslopes must be the dominant erosional processes in the study basins. Lack of bare ground and the presence of highly permeable soils indicate that channel erosion probably dominates over erosional processes operating on hillslopes. Erosional landforms were mapped previously (Deborah Harden, Department of Geology, California State University, San Jose, written commun., 1985). In light of the field evidence, a workplan was established to quantify channel erosion and deposition, which have been poorly documented for most previous sediment budgets.

Rates of channel erosion and deposition in Lake Tahoe tributaries studied for this report were quantified by repetitive surveys of a network of stream-channel cross sections. These measurements provide data only on the cross-sectional area of channel erosion or deposition at a single point; they must be extended horizontally (upstream and downstream) to estimate volume change, which can then be converted to sediment weight. Rates determined at channel cross sections were extrapolated to all active channels in a given basin by inventorying areas of eroding streambanks and active channels along selected channel reaches.

Channel-inventory data collected in the study basins provided a much better mechanism for generalizing cross-sectional data to entire channel systems than if data were available only at cross-sectional sites. Channel inventories provided data on eroding bank area and on channel area actively transporting water and sediment. Such data are generally unavailable for most sediment budgets. Where possible, sample reaches were contiguous. Where channel length or dense channel growth precluded mapping of contiguous reaches, only selected reaches were mapped. Data from these selected reaches were then applied to uninventoried channels of the same size and in roughly the same position within the basin.

Because it was known from available sediment-yield data (U.S. Geological Survey, 1975, 1976, 1977, 1978, 1979, 1981a, 1981b, 1982; Fogelman and others, 1984, 1985a, 1985b) that erosional processes operate relatively slowly in the Lake Tahoe basin, the study was designed to collect data for 4 years. It was hoped that this 4-year period would allow for measurable change to occur in sediment source areas and would allow enough time for significant runoff and sediment-discharge events to occur during the study. By quantifying what were believed to be the most important processes in the mobilization, transport, and storage of sediment, it was hoped that sediment budgets for the four Lake Tahoe tributaries could be produced without relying on a residual term to balance the sediment budgets. Further detail on methods used to develop sediment budgets for the study basins is contained in the section, "Development of the Suspended-Sediment Budgets."

## DESCRIPTION OF THE STUDY AREAS

### LAKE TAHOE BASIN

The Lake Tahoe basin lies on the east side of the Sierra Nevada crest between the main range of the Sierra Nevada on the west and the Carson Range on the east (fig. 1). Altitude of the basin ranges from about 1,900 m above sea level at lake level to about 3,300 m. Hydrologically, the Lake Tahoe basin forms the upper part of the Truckee River basin, which empties into Pyramid Lake in Nevada. The Lake Tahoe basin has an area of about 1,310 km$^2$ of which Lake Tahoe occupies nearly 500 km$^2$ (Crippen and Pavelka, 1970). The four tributary basins included in this study comprise about 8 percent of the Lake Tahoe basin area (exclusive of the lake).

The Lake Tahoe basin was formed by a downdropped fault block followed by volcanic activity on the north side of the basin (Crippen and Pavelka, 1970). Igneous rocks underlie most of the basin; granitic rocks are more common along the west, south, and east shores; and volcanic rocks are more evident along the north shore of the lake (Matthews and Burnett, 1971). A roof pendant of metamorphic rocks forms the crest of the Sierra Nevada on the northwest side of the lake (Matthews and Burnett, 1971). The western part of the Lake Tahoe basin was heavily glaciated during the Pleistocene; however, the eastern part shows no evidence of glaciation (Hyne and others, 1972).

Climatic records are available for only a small number of sites in the Lake Tahoe basin, and no climatic data exist for the individual study basins. The climate of the Lake Tahoe basin, in general, was described by Crippen and Pavelka (1970), and the following summary is based on their account. Temperatures range between -26 and 34 °C. Mean annual temperature is 5.8 °C. Winters are cold, and heavy accumulations of snow are common. Summers generally are warm, but nighttime temperatures can fall to near freezing throughout the season. Daily low temperatures fall to or below freezing an average of 220 days per year at Tahoe City, California (fig. 1). About 50 percent of the precipitation at low altitudes and 90 percent at altitudes above 2,400 m falls as snow during the winter, and generally only slight amounts of precipitation fall during summer thunderstorms (Crippen and Pavelka, 1970). The long-term average annual snowfall at Tahoe City is 5,400 mm.

Weather patterns are strongly affected by prevailing winds, as modified by the Pacific Ocean, the Sierra Nevada, the Carson Range, and local topography. Winter storms generally move eastward from the Pacific Ocean, and snow falls most heavily on the western side of the Lake Tahoe basin. Average annual precipitation is as high as 2,280 mm at higher altitudes on the west side of the lake. Average annual precipitation is only 1,010 mm on the east side of the lake. Owing to the movement of warm marine airmasses, snow level may vary during and between storms. Rain is possible at lower altitudes throughout the winter, and the largest known regional streamflows have been triggered by heavy rains falling on snow. Snow accumulations are greatest and most persistent on north-facing slopes and at high altitudes. For example, snow depth as great as 6,200 mm was recorded as late as April 1 on the west side of the lake at an altitude of 2,500 m. There are no perennial snow fields or glaciers in the basin.

Plant communities in the Lake Tahoe basin were mapped by the Tahoe Regional Planning Agency (1971a), and the following description is based on that work. The vegetation of the Lake Tahoe basin is predominantly coniferous forest; on the wetter, west side of the basin, the forest communities are composed primarily of white and red fir, but on the east side, ponderosa pine is predominant. Shrub communities are found on drier sites, such as south-facing exposures. Common shrubs are ceanothus and manzanita. Riparian communities occur along stream channels, in meadows, and along the lake shore in some locations. Riparian communities include herbaceous species (sedges and rushes) and woody species (red alder, dogwood, willow, cottonwood, and aspen).

## STUDY BASINS

### BLACKWOOD CREEK

The Blackwood Creek basin lies on the west side of Lake Tahoe (figs. 1 and 2). With a drainage area of 29.8 km$^2$, it is the fourth largest basin tributary to the lake. The crest of the Sierra Nevada forms the western edge of the basin (Tahoe Regional Planning Agency, 1971b). Average annual precipitation in the Blackwood Creek basin is 1,400 mm (Hill and others, 1990). Bedrock of the Blackwood Creek basin is mostly composed of volcanic rocks in the northern half of the basin and metamorphic rocks in the southern part (David Harwood, U.S. Geological Survey, written commun., 1986). The basin was heavily glaciated during the Pleistocene (Hyne and others, 1972), and large volumes of outwash material are stored in downstream areas of the basin, where these glaciofluvial deposits form the flat valley floor. Channels of low-order streams are composed of varying amounts of bedrock and alluvium. The main channel of Blackwood Creek, which is 9.8 km long (Hill and others, 1990), flows primarily through alluvial and glaciofluvial deposits. Vegetation in the basin reflects moist conditions, except for several south-facing slopes, which are underlain by volcanic rocks and are devoid of vegetation. Forest communities are primarily composed of white and red fir and lodgepole pine. Large areas on south-facing slopes are covered by shrub species such as ceanothus and manzanita. Riparian communities are found along stream channels and on the low-gradient valley floor in the lower canyon. Average land-surface slope is 17.8° (Hill and others, 1990). Depositional landforms include active and inactive alluvial fans and talus. Erosional landforms include debris slides and snow avalanche scars (Deborah Harden, Department of Geology, California State University, San Jose, written commun., 1985).

The Blackwood Creek basin has been affected by four major land uses: grazing, logging, recreation--most notably off-road vehicle (ORV) activity--and gravel mining. No residential or commercial development has occurred upstream from the gaging station, which is about 0.5 km upstream from Lake Tahoe.

Sheep grazing began in the Blackwood Creek basin in 1864 and continued until 1962 (Andrea Holland, U.S. Forest Service, written commun., 1987). Cattle were pastured intermittently in the basin during

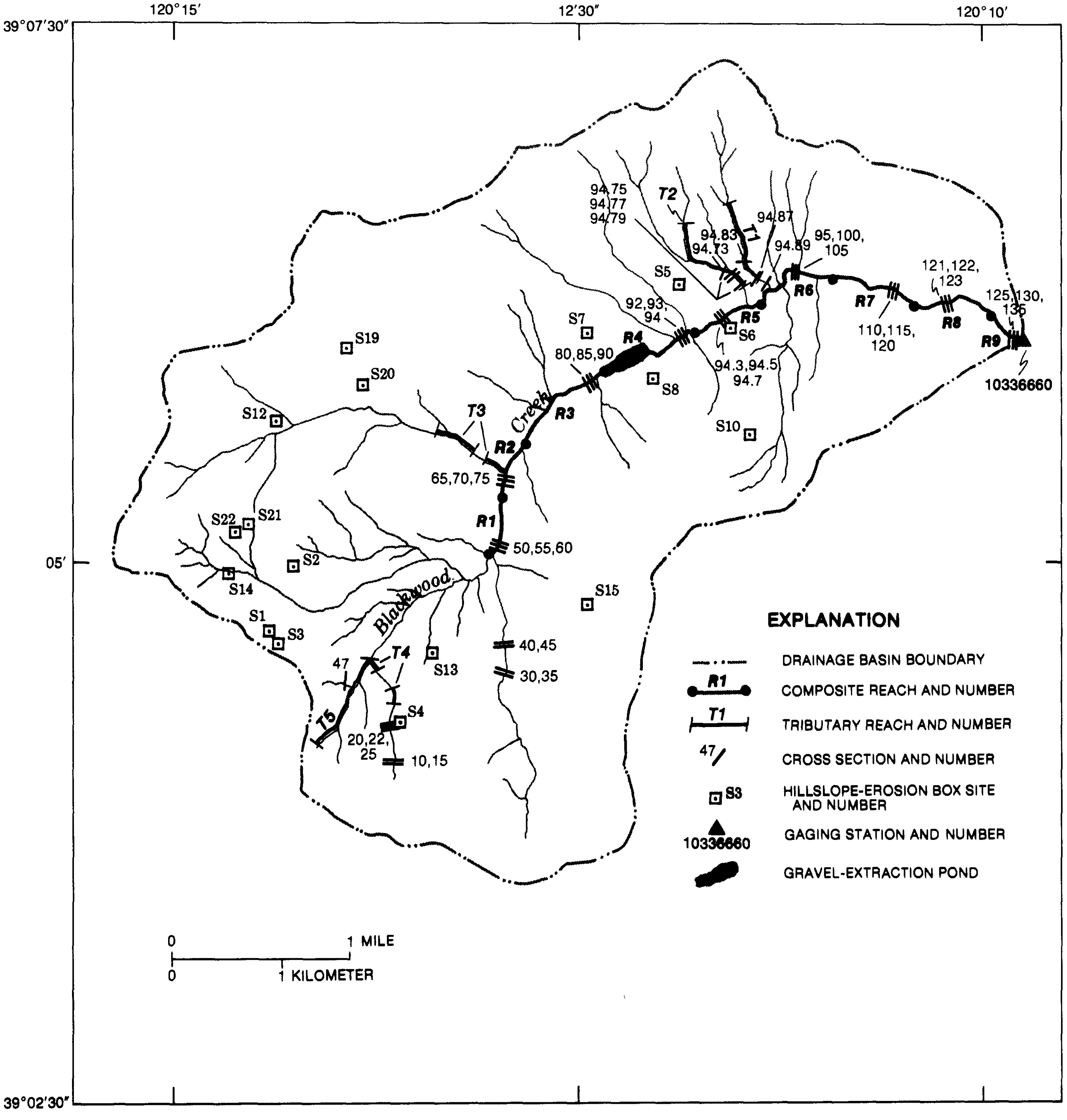

**Figure 2.** Location of composite reaches, tributary reaches, cross sections, hillslope-erosion sites, and gaging station, Blackwood Creek basin.

this period. Concerns over grazing effects were expressed as early as 1905, and a 1944 report by the U.S. Forest Service indicated widespread loss of meadow forage due to overgrazing and associated gullying, gravel deposition on meadow surfaces, and invasion of meadow areas by lodgepole pine (Andrea Holland, U.S. Forest Service, written commun., 1987). The areas of the Blackwood Creek basin most severely affected by grazing probably are the meadows along the lower channel (fig. 2, reaches 7 and 8) and south-facing slopes in the upper basin where some of the present bare ground may have been covered with herbaceous vegetation and topsoil prior to grazing (Andrea Holland, U.S. Forest Service, written commun., 1987).

Parts of the Blackwood Creek basin were logged in the late 1800's and again between 1953 and 1970 (Andrea Holland, U.S. Forest Service, written commun., 1987). A map in a report by Suhr (1971) indicates that forests in roughly two-thirds of the basin were logged during this later period. Logging activity was especially heavy on the alluvial fans and flood plains in the lower canyon and on north-facing slopes. A sawmill was operated in the basin beginning in 1956. Logging in the Blackwood Creek basin ended in 1970, but haul roads and skid trails are still evident. Road-associated gullies were noted by Suhr (1971). According to David Blanchett (U.S. Forest Service, written commun., 1987), logging-related erosion in the Blackwood Creek basin, including road-related erosion, is minor at present. In the course of fieldwork for this study, water was observed flowing along roads and mobilizing sediment during snowmelt and rainstorms. Many apparently active gullies were noted along roads and trails, and former haul-road surfaces had lost much of their fine-grained fill to erosion.

Although roads are no longer used for logging in the Blackwood Creek basin, many kilometers of former logging roads remain passable. Some roads will be kept open as "designated routes" for ORV users under present U.S. Forest Service management. Unsanctioned operation of vehicles also occurs, including ORV operation in and near the stream channel and meadows. Abandoned haul roads also are used by hikers, equestrians, and bicyclists. A traditional, but unofficial, camping area near the site of the former gravel-extraction pond presently is being upgraded (fig. 2).

From 1960 to 1968, a gravel-extraction operation was located about 4 km from the mouth of Blackwood Creek (fig. 2). An estimated total of about 40,000 $m^3$ of material was removed from streamside deposits, and the stream channel was diverted into an artificial channel to the south of the original channel. Suhr (1971) observed significant bank erosion along the artificial channel. In 1979, the U.S. Forest Service completed a diversion channel to redirect the stream into its original channel, which had been enlarged by gravel extraction. Presently, this reach of the stream forms a series of ponds and seems to act as a sediment trap.

The U.S. Forest Service has buttressed banks with native vegetation, lined gullies with rocks, and seeded bare slopes at a few down-valley locations to reduce sediment loads, improve water quality, and enhance fisheries (Albert Todd, U.S. Forest Service, oral commun., 1987). Effects of these efforts on the processes monitored for this study are unknown. Rehabilitation work began during the winter of 1986-87. Results described in this report reflect processes monitored during 1983-87 and may not represent conditions after rehabilitation.

Among the streams studied for this report, Blackwood Creek has the highest streamflow and suspended-sediment yield for 1984-87 (table 1). For the periods of available record at station 10336660 (fig. 2), average annual streamflow was 1,157 mm (1961-85), and average annual suspended-sediment yield was 80.4 $Mg/km^2$(1975-85).

### GENERAL CREEK

The General Creek basin (figs. 1 and 3), with a drainage area of 19.3 $km^2$, is on the west side of Lake Tahoe a few kilometers south of the Blackwood Creek basin. Precipitation patterns are roughly similar to those in Blackwood Creek, and snowfall also is heavy during the winter. Average annual precipitation is 1,270 mm, slightly less than in the Blackwood Creek basin (Hill and others, 1990). In contrast to the Blackwood Creek basin, bedrock consists of glaciated granite (Matthews and Burnett, 1971). The upper basin contains numerous landforms resulting from glacial erosion. The lower-basin morphology results largely from deposition of morainal till along basin margins and till and outwash deposits

**Table 1.** Instantaneous peak streamflow, streamflow, suspended-sediment discharge, and suspended-sediment yields for the four study basins, 1984-87

[Data were previously published by Fogelman and others, 1985b; Hunter, Mullen, Simpson, and Grillo, 1987, 1988; Hunter, Mullen, and Simpson, 1988. $km^2$, square kilometer; $m^3/s$, cubic meter per second; mm, millimeter; Mg, megagram; $Mg/km^2$, megagram per square kilometer. --, does not apply]

| Basin (fig. 1) | Drainage area ($km^2$) | Water year | | | | Average annual (1984-87) |
|---|---|---|---|---|---|---|
| | | 1984 | 1985 | 1986 | 1987 | |
| | | Instantaneous peak streamflow ($m^3/s$) | | | | |
| Blackwood Creek ....... | 29.8 | 15.5 | 5.7 | 46.4 | 4.8 | -- |
| General Creek ......... | 19.3 | 10.2 | 3.6 | 15.1 | 2.9 | -- |
| Edgewood Creek ....... | 8.3 | .15 | .22 | .62 | .12 | -- |
| Logan House Creek ..... | 5.4 | .10 | .11 | .18 | .08 | -- |
| | | Streamflow (mm) | | | | |
| Blackwood Creek ....... | 29.8 | 1,670 | 783 | 1,690 | 466 | 1,150 |
| General Creek ......... | 19.3 | 1,110 | 539 | 1,190 | 294 | 783 |
| Edgewood Creek ....... | 8.3 | 380 | 228 | 304 | 190 | 276 |
| Logan House Creek ..... | 5.4 | 175 | 117 | 175 | 58 | 131 |
| | | Suspended-sediment discharge (Mg) | | | | |
| Blackwood Creek ....... | 29.8 | 1,290 | 355 | 6,300 | 161 | 2,030 |
| General Creek ......... | 19.3 | 165 | 45.6 | 578 | 16.5 | 201 |
| Edgewood Creek ....... | 8.3 | 52.7 | 28.4 | 69.7 | 10.3 | 40.3 |
| Logan House Creek ..... | 5.4 | 3.9 | 2.6 | 7.0 | 1.5 | 3.8 |
| | | Suspended-sediment yield ($Mg/km^2$) | | | | |
| Blackwood Creek ....... | 29.8 | 43.3 | 11.9 | 211 | 5.4 | 67.9 |
| General Creek ......... | 19.3 | 8.5 | 2.4 | 29.9 | .9 | 10.4 |
| Edgewood Creek ....... | 8.3 | 6.3 | 3.4 | 8.4 | 1.2 | 4.8 |
| Logan House Creek ..... | 5.4 | .7 | .5 | 1.3 | .3 | .7 |

along the valley floor. In the upper part of the basin, the main channel of General Creek, which is 14.6 km long (Hill and others, 1990), consists of varying amounts of bedrock, boulders, and alluvium. Along lower reaches, the main channel is cut mostly through alluvial and glaciofluvial deposits. The width of the basin is small relative to its length, and there are few tributary streams. Riparian vegetation, mostly alders and willows, covers a large area of the basin; the rest of the basin is covered by coniferous forest. The average land-surface slope is 12.2° (Hill and others, 1990). Erosional landforms include possible debris slides. Depositional landforms are restricted to talus.

The land-use history of the General Creek basin is not well documented. Apparently, logging took place in the basin--probably in the 1800's and 1950's. The basin also may have been grazed by sheep or cattle, but the extent and duration are unknown. Ownership of the basin has been public for many years. The lower basin is included within Sugar Pine Point State Park, and the upper basin is mostly within the Desolation Wilderness Area managed by the U.S. Forest Service. Recreational activities by campers and hikers are the primary land use. Development has been limited to a few paved surfaces and buildings in the campground area near the mouth of the stream.

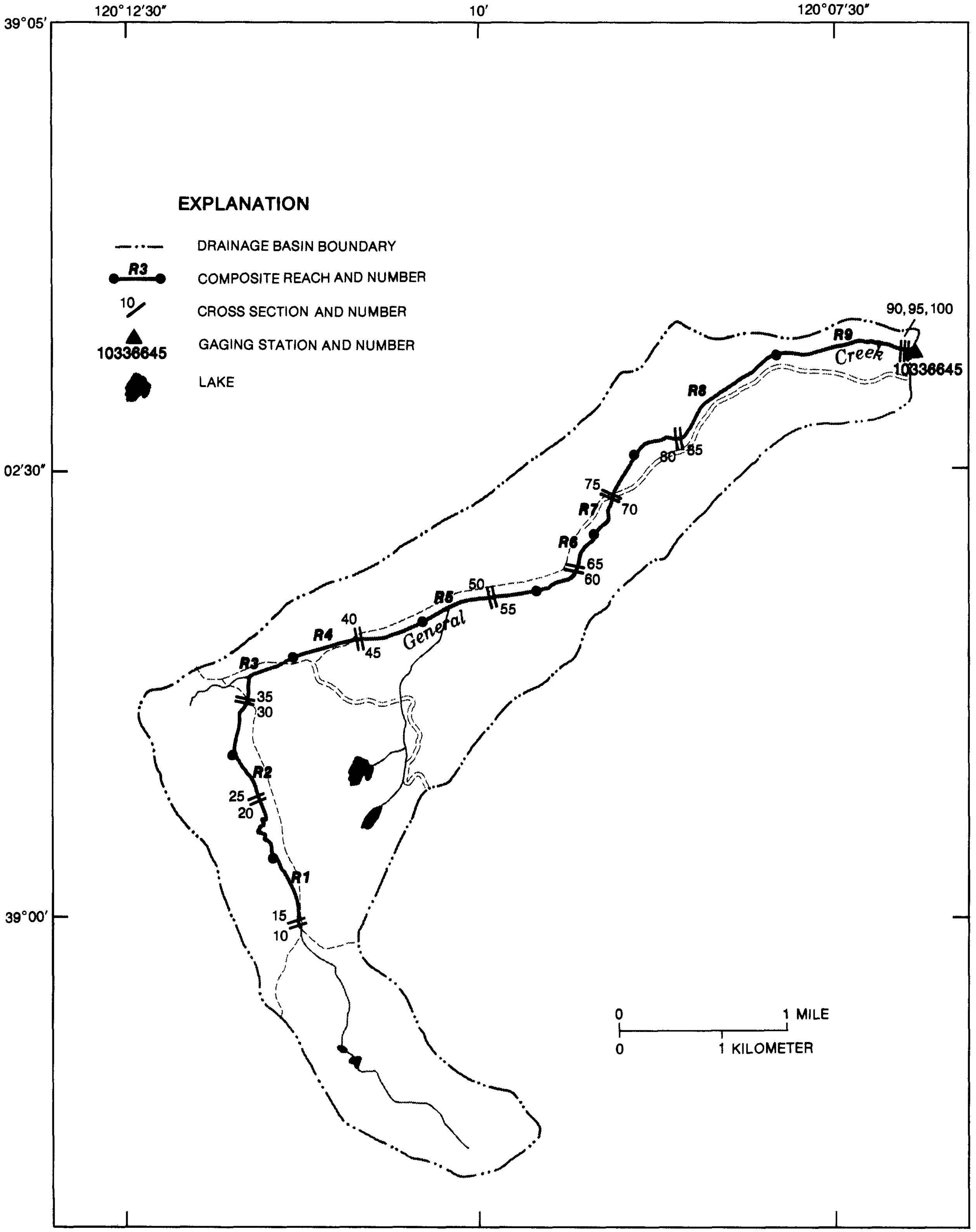

**Figure 3.** Location of composite reaches, cross sections, and gaging station, General Creek basin.

Compared to the other streams discussed in this report, General Creek has intermediate values of streamflow and suspended-sediment yield for 1984-87 (table 1). Streamflow and suspended-sediment data have been collected at station 10336645 (about 0.6 km upstream from the lake) since 1981. Average annual streamflow for the period of record (1981-87) was 949 mm, and average annual suspended-sediment yield for the same period was 17.6 Mg/km$^2$.

### EDGEWOOD CREEK

The Edgewood Creek basin, which has a drainage area of 8.3 km$^2$, is on the southeast side of Lake Tahoe, on the western flank of the Carson Range (figs. 1 and 4). Because it is located in the rain shadow of the Sierra Nevada to the west, average annual precipitation in the Edgewood Creek basin is 584 mm, which is less than half of the precipitation in the westside basins (Hill and others, 1990). Bedrock consists entirely of decomposed granite (Matthews and Burnett, 1971). The basin was not glaciated, and thus lacks the large volume of stored sediment and flat valley floors that characterize the lower reaches of the Blackwood Creek and General Creek basins. The average land-surface slope is 17.7° (Hill and others, 1990). In some locations, channels are tightly confined in narrow V-shaped valleys between steep hillslopes. Erosional landforms mapped in the Edgewood Creek basin include debris slides and rockfalls. Depositional landforms include talus. Vegetation is primarily coniferous forest, consisting mostly of ponderosa pine. Cover density generally is low, reflecting the precipitation regime. A narrow riparian zone is thickly covered with alder, willow, and dogwood, and there are several small flood-plain meadows. The main channel of Edgewood Creek is 7.4 km long.

Much of the Edgewood Creek basin has been developed for residential and commercial purposes. The basin is bisected by Kingsbury Grade, a major traffic route in the Lake Tahoe area (fig. 4). Commercial development is concentrated in the lower basin near U.S. Highway 50, downstream from the gaging station, which is about 2.3 km upstream from the lake. Many homes and a major ski area have been built in the upper basin. Most of this development has occurred since 1950 (Crippen and Pavelka, 1970). In addition, the Edgewood Creek basin has been affected by ORV use, quarrying, and road and sewer-line construction. Edgewood Creek basin is the only study basin affected by residential and commercial development.

Streamflow and suspended-sediment yields in the Edgewood Creek basin are lower than in the west-side basins for 1984-87 (table 1). Streamflow and sediment records for station 10336759 are available for 1983-87. Average annual streamflow for the period of record was 316 mm, and average annual suspended-sediment yield was 13.3 Mg/km$^2$.

### LOGAN HOUSE CREEK

Logan House Creek basin, with a drainage area of 5.4 km$^2$, is the smallest study basin (figs. 1 and 5). It is on the east side of Lake Tahoe and several kilometers north of the Edgewood Creek basin, which it resembles in climate and geology. Average annual precipitation is 635 mm, more than in the Edgewood Creek basin (Tahoe Regional Planning Agency, 1971b). Bedrock is chiefly decomposed granite, but parts of the upper basin are underlain by metamorphic rocks (Matthews and Burnett, 1971). The main channel is 3.5 km long (Hill and others, 1990). The Logan House Creek basin was not glaciated. Like the Edgewood Creek basin, it has steep slopes adjacent to channels and little sediment stored along lower reaches. The average land-surface slope is 15.0° (Hill and others, 1990). The only erosional landform mapped in the basin is a debris slide (Deborah Harden, Department of Geology, California State University, San Jose, written commun., 1985). Vegetation is similar to that of the Edgewood Creek basin, except that several large areas of riparian vegetation, predominantly alder, aspen, and herbaceous meadow species, occur in greatly sloping areas below numerous perennial springs.

The Logan House Creek basin was partly logged in the 1800's as evidenced by decomposing stumps, unused roads, and skid trails. The precise areas and duration of logging operations are not known. Other than this logging activity, the basin seems undisturbed by human activity. There is no residential or commercial development upstream from the gaging station, 0.7 km upstream from the lake. Only one unsurfaced road passes through the basin and recreational use is light.

Streamflow and suspended-sediment yields for the Logan House Creek basin are the lowest of the four basins studied (table 1). Streamflow and sediment data at station 10336740 are available for 1984-87. Average annual streamflow for this period was 131 mm, and average annual suspended-sediment yield was 0.7 Mg/km$^2$ (table 1).

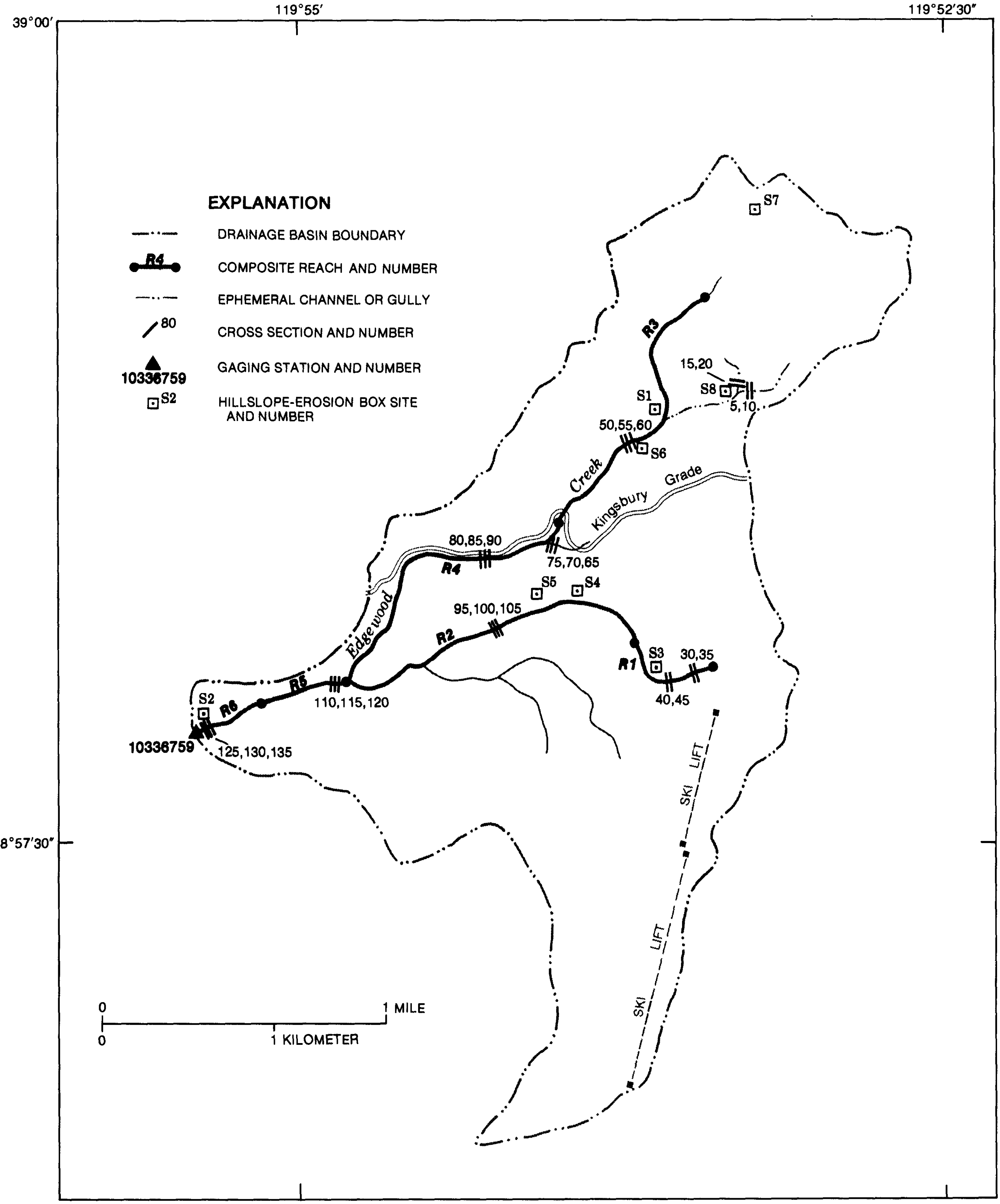

**Figure 4.** Location of composite reaches, cross sections, hillslope-erosion sites, and gaging station, Edgewood Creek basin.

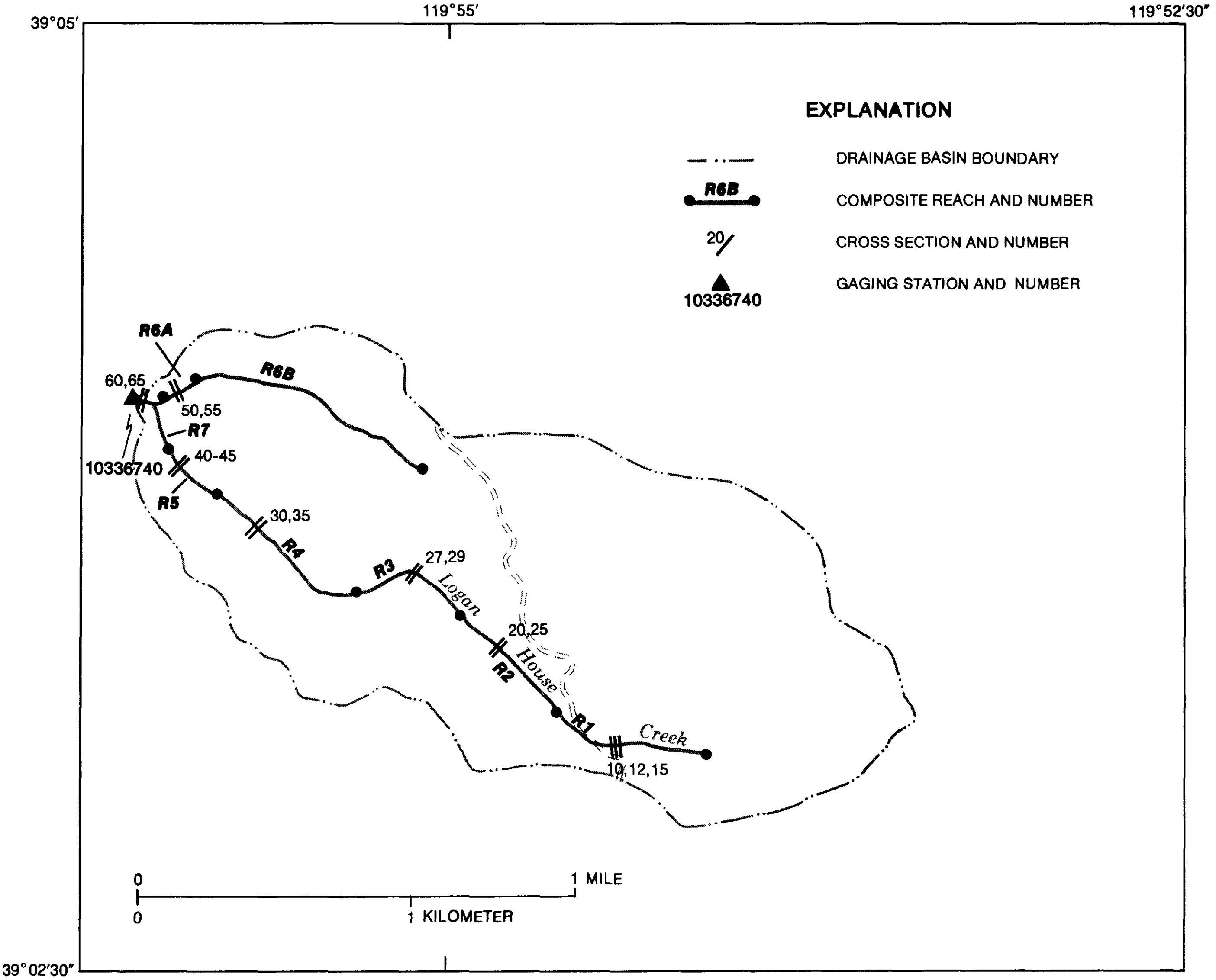

**Figure 5.** Location of composite reaches, cross sections, and gaging station, Logan House Creek basin.

## STREAMFLOW CONDITIONS DURING STUDY

Streamflow conditions varied widely during the study. Streamflow during 1984 and 1986 was relatively high, and streamflow during 1985 and 1987 was relatively low (table 1). Table 2 presents recurrence intervals, or the average interval of time a given flow will be equaled or exceeded, for instantaneous peak streamflow measured at the Blackwood Creek gaging station. In the other three study basins, the period of record for streamflow is not long enough to estimate recurrence intervals.

## DEVELOPMENT OF THE SUSPENDED-SEDIMENT BUDGETS

Drainage-basin sediment budgets are quantitative expressions of the relations between rates of sediment mobilization and sediment storage within a drainage basin during a defined period of time and sediment discharge from the basin during the same period. Sediment budgets are based on the assumption that the law of mass balance applies to sediment during the time period included in the sediment budget, that is, sediment mobilization (input to the channel system

**Table 2.** Instantaneous peak streamflow and suspended-sediment discharge, Blackwood Creek, 1984-87

[Recurrence intervals estimated using procedures described by U.S. Water Resources Council (1981) using streamflow data collected 1961-88. $m^3/s$, cubic meter per second; Mg/d, megagram per day]

| Water year | Instantaneous peak streamflow ($m^3/s$) | Recurrence interval (years) | Suspended-sediment discharge (Mg/d) |
|---|---|---|---|
| 1984 | 15.5 | 2.4 | 187 |
| 1985 | 5.7 | 1.2 | 26.2 |
| 1986 | 46.4 | 11 | 2,630 |
| 1987 | 4.8 | 1.1 | 21.3 |

from erosion of hillslopes and channel banks and bed) equals sediment discharge (output from the channel system at the basin mouth) after changes in storage are considered.

A generalized sediment budget would satisfy the equation:

$$QS = MS - SS \qquad (1)$$

where

$QS$ is sediment discharge,
$MS$ is mobilized sediment, and
$SS$ is stored sediment.

Sediment mobilization is generally determined through field monitoring of erosional processes; these measurements therefore reflect the amount of sediment mobilized but may not provide direct evidence of sediment discharged to stream channels. Changes in sediment storage are determined with repetitive field measurements of sediment-storage sites, such as channel beds, channel bars, and accumulation behind organic debris. Sediment discharge, in most cases, is assumed to be equal to fluvial sediment discharge at the mouth of the basin, which is determined using established methods (Porterfield, 1972). The sediment budgets discussed in this report were calculated using field data collected annually and averaged over the 4-year study period (1984-87) to provide estimates of average annual budgets. Measured annual suspended-sediment discharge at the gaging stations were averaged over the 4-year study period and compared to estimated sediment discharge from sediment-budget calculations.

Sediment budgets can be developed for total sediment or for a specific size fraction of the total sediment load. The sediment budgets developed here are restricted to sediment finer than 2-mm intermediate-grain diameter, that is, to the sand, silt, and clay fractions. The size fraction less than 2 mm was selected because nearly all sediment carried in suspension in the four study streams is finer than 2 mm (Hunter, Mullen, and Simpson, 1988), and because fine sediment generally is of greatest concern for nutrient transport (Sharpley, 1986; Young and others, 1986). Thus, the budgets are referred to as suspended-sediment budgets. Possible errors introduced by restricting the sediment budgets to the sand, silt, and clay fractions are discussed at the end of this section.

The conceptual model of sediment transport used as the basis of the sediment budgets can be expressed as follows: sediment is mobilized from hillslopes by surficial erosional processes and transported to low-order tributaries; within low-order tributary channels, this sediment is carried downstream to higher order channels along with sediment mobilized by erosion of tributary banks and beds; within the higher order channels, sediment contributed by tributaries adds to sediment mobilized within the higher order channel by erosion of banks and bed; some or all of this sediment may be stored along the streambed.

Field observations indicated that several potential sediment-transport or storage processes were relatively unimportant in the four study basins. Bank deposition apparently was negligible along both tributary and main channels. Deposition along the streambeds of tributary channels seemed insignificant due to high channel gradients. Hillslope erosion seemed to be limited to surficial processes such as slope wash, soil creep, and dry ravel. Transport of sediment from hillslopes to channels was noted only where hillslopes are immediately adjacent to channels; in places where hillslopes are separated from channels by wide, flat valley floors, hillslope-sediment delivery was considered negligible. Landslides are rare in the four study basins, and no significant landslide activity was observed during the study. The sediment budgets included determinations of erosion of hillslope surfaces, tributary banks and beds, and main-channel banks. Erosion and deposition were determined along main-channel beds.

## GROSS AND ROUTED SUSPENDED-SEDIMENT BUDGETS

Sediment discharge measured at gaging stations near the basin mouths was compared to sediment discharge estimated using the suspended-sediment-budget approach, to determine whether or not the budget was "balanced." If all erosional or depositional processes were adequately quantified, sediment discharge estimated using the budget approach should closely match measured sediment discharge. Two types of sediment budgets were produced for each basin. First a "gross" sediment budget was estimated. This budget simply represents the amount of sediment eroded by all processes, minus the amount of sediment deposited along main-channel beds. Data used to estimate gross sediment budgets were used to extend the analysis to produce "routed" sediment budgets. These routed sediment budgets were determined by defining sections, termed "composite reaches," of the main channels in each basin and estimating sediment mobilization, storage, and discharge within each composite reach. The routed sediment budget provides a check on gross sediment budgets by identifying reaches where budget calculations may not balance. Providing a reach-by-reach accounting of where sediment is eroded or deposited, the routed sediment budgets provide information on where most sediment is eroded or deposited within each basin.

For routed sediment budgets, sediment accounting by reach requires quantification of sediment sources and storage for each reach. Possible sources of sediment for composite reaches include erosion of hillslopes, tributaries, and channel banks and bed within the composite reach, and sediment mobilized from the adjacent upstream composite reach (except in the case of the uppermost reach). Any sediment in excess of that required to fulfill the estimated storage due to bed deposition within a composite reach is assumed to be transported to the next downstream reach. If estimated sediment storage within a composite reach is in excess of the sediment supplied from the upstream composite reach, tributaries, and bank and bed erosion within the composite reach, net discharge from the composite reach is assumed to be zero and reflects possible errors in the suspended-sediment budget. Estimated sediment discharge from the lowermost reach represents the sediment output determined by the routed sediment budget. Sediment output estimated in this manner can then be compared with sediment output estimated with basinwide process calculations (gross sediment budgets) and with sediment discharge measured at the gaging station. This sediment-output comparison can be used to determine if the sediment budget gives a reasonable approximation of how sediment is mobilized, transported, or stored within the drainage basin.

## HILLSLOPES

### EROSION BOXES

Erosion boxes (fig. 6) were installed at several sites in the Blackwood Creek and Edgewood Creek basins to measure directly the rate of sediment transport on hillslopes. Erosion-box sites (figs. 2 and 4) were on north and south aspects, in three slope classes (less than 15°, 15-25°, and greater than 25°), and in three cover classes (bare, shrub, and forest). Slope and cover-class data were presented by Hill and Nolan (1990).

Numerous difficulties with these boxes, most notably vandalism, frost heaving, and crushing due to snow accumulation, necessitated experimentation with several designs for the erosion boxes. All boxes were 0.3 m long and were installed along hillslope contours flush with the ground surface. Boxes were either uncovered galvanized steel boxes (fig. 6), metal-covered boxes, or galvanized steel boxes covered with plywood. The uncovered boxes were not limited to any size range of sediment. Owing to the size of the slot between box and cover, the metal-covered boxes could accommodate only particles smaller than 20 mm, and the plywood-covered boxes were limited to particles smaller than 40 mm. All boxes had small holes on their upslope sides to allow water to exit; on the uncovered and metal-covered boxes, the holes were screened with a 0.032-mm mesh. Plywood-covered boxes were not screened.

The hillslope-sediment-transport rate was calculated as the amount of sediment finer than 2 mm per unit of hillslope per year. Each erosion box was

Figure 6. Uncovered erosion box.

examined yearly, and any accumulated sediment was removed and oven dried or air dried. Samples were weighed, placed on a 2-mm sieve, and mechanically shaken for 10-20 minutes. Sediment remaining on the sieve was weighed and then subtracted from the total sample mass.

### GULLIES

Gullies were mapped in parts of the Blackwood and Edgewood Creek basins. A gully generally is defined as a small channel produced by running water in earth or unconsolidated material (Bates and Jackson, 1984, p. 227). In this report, a gully is defined as any channel having steep sides, a depth greater than 0.3 m, a width-depth ratio of 3.0 or less, and apparently active headward erosion or clear association with disturbances, such as road drainage. Gully dimensions were measured with a range finder or surveying rod; precisions are equivalent to those for channel inventories (see p. 17).

Most gullies were too small to be visible on the aerial photographs and were located using field traverses. Gully locations were noted on topographic maps by comparing features identified on aerial photographs with those visible on the ground and occasionally by taking compass bearings on landmarks.

Two samples of gully bank material were collected in the Blackwood Creek basin to estimate bulk density and percentage of material finer than 2 mm, as described for channel banks (see p. 17). Total suspended-sediment contributions from gullies mapped in the Blackwood Creek basin over the unknown period of time since gully initiation were then estimated. Suspended-sediment contributions from gullies in the Edgewood Creek basin were based on bulk densities of streambed and streambank samples collected along Edgewood Creek.

## CHANNELS

### CHANNEL CROSS-SECTIONAL SURVEYS

Channel cross sections were established to determine changes in streambank and bed cross-sectional areas due to bank erosion and bed scour and fill. The cross sections were located along the main channels of each stream and along several tributary streams in the Blackwood Creek and Edgewood Creek basins; they were located in groups of two or three at approximately equal intervals along the channels to document changes representative of each reach. Locations of cross-sectional groups for each basin are shown in figures 2-5. Within cross-sectional groups, individual cross sections were located at distances of two or three channel widths from adjacent cross sections.

Cross sections were monumented with lengths of metal fencepost or reinforcement rod (rebar). The elevation difference between the tops of the monuments was determined with a level and surveying rod. Compass bearings were taken from one monument to the other, and the distance between monuments was recorded; this was done to allow reestablishment of the cross section if one of the two monuments was lost. In addition, reference marks were established at most cross sections to provide a means of relocating monuments. Monuments were marked by drilling small holes into the fenceposts or twisting wire on the rebar to provide a consistent position for attaching the cloth tape during surveys.

Two methods were used to survey cross sections. At wide cross sections (generally wider than 25 m), a self-leveling level and rod were used to obtain elevations. A small bubble level was used to keep the rod vertical. Elevations were measured to the nearest 3 mm. Distances between monuments were read to the nearest 0.03 m with a cloth tape. At cross sections of lesser width, where sagging of the cloth tape was not significant, elevations were determined by holding the rod vertically against the cloth tape and reading the rod where it intersected the lower edge of the cloth tape. Precision of measurement for both distances and rod readings was 3 mm. These two methods of surveying are referred to as "level" and "tagline," respectively. No distinction is made in figures 2-5 between cross sections measured by these two methods.

Cross-sectional data were entered into computer files and processed by a series of programs that converted the data from inch-pound into International System (SI) units, corrected horizontal distances for the differences between monument elevations (for the slope of the cloth tape), sorted the data, and plotted the most recent survey with the previous survey at the same cross section. Locations of upper and lower extents of banks were determined from these plots and from notes made during fieldwork. On the basis of these locations, the changes in cross-sectional area between successive surveys for the left and right banks and bed were calculated with a computer-graphics program. The rates of horizontal bank change and vertical bed scour and fill were calculated by dividing the change in cross-sectional area measured at each bank by the height of that bank or by dividing change in cross-sectional area measured at the bed by the horizontal distance between the base of each bank. The average rate of bank and bed change monitored during the 4-year study period was calculated for each cross section as the sum of annual changes, divided by four. These data then were combined with results of other monitoring activities for the four study basins (see p. 18) to account for variations in basin characteristics and sampling densities.

For the calculations of bank erosion, rates were considered to be zero when average rates were less than the precision limits of the horizontal distance measurement (±3 mm for tagline sections and ±30 mm for level sections). Negative changes in bank cross-sectional areas (apparent movement of the bank toward the channel) were interpreted as no erosion. Negative bank changes (no erosion) most likely represent the growth of plants and moss on banks. Such growth could easily represent significant cross-sectional area changes during the study because the rate of plant growth could equal or exceed the low rates of bank erosion.

On the basis of field observations, sediment is not deposited or "plastered" on bank faces in the study basin, and negative change in bank cross-sectional area (deposition) did not result from this process. Schumm (1961) found that bank plastering does not occur unless streambank and streambed material are highly cohesive and contain a high percentage of silt- and clay-sized material. Bank formation presumably begins as channel-bed deposition. Material deposited on the bed is eventually incised and new or larger banks are left behind. For this study, bank deposition by this process has been measured as bed deposition.

### CHANNEL INVENTORIES

Stream channels were inventoried to determine areas of eroding and stable streambanks, areas of the streambeds, and volumes of sediment storage in the channels. These inventories were conducted by walking along stream channels, measuring the dimensions of the channel and of sediment storage sites, such as active channel bars and accumulated organic debris, and visually estimating the percentage of each bank that seemed to be eroding.

Measurements were made in short contiguous sections of the stream channels, termed reaches (for details on reaches, refer to Hill and others, 1990). In the Blackwood and General Creek basins, the entire lengths of the main channels were inventoried. In the Edgewood and Logan House Creek basins, thick riparian vegetation made an inventory of the entire main channels impractical; instead, about 30 percent of the lengths of the main channels were inventoried in reaches near groups of channel cross sections, and results were extrapolated to the remainder of the channel.

Reach length was measured with a range finder or surveying rod. Bank height and streambed width were measured with a range finder or surveying rod at four to eight locations and averaged for each reach. Dimensions of sediment-storage sites, which include channel storage above the channel thalweg, channel bars, and prisms stored behind accumulated organic debris, were measured with a surveying rod and summed for each reach. Measurement precision for rod measurements was 0.03 m. For range-finder measurements, precision varied between 0.15 and 1.5 m, and precision decreased with distance.

The percentage of the total length of streambank within each reach that seemed to be actively eroding was estimated by inspection. Exposed roots, vertical and unvegetated banks, and slumping or undercutting were considered to be evidence of active bank erosion. The area of eroding bank for each reach was computed as reach length multiplied by average bank height, and by the percentage of bank length estimated to be actively eroding, divided by 100. Results for right and left banks were summed to give the total area of eroding banks in each reach. Streambed area was computed as reach length multiplied by average bed width.

### BANK AND BED SAMPLING

Samples of streambank and streambed material were collected at each cross-sectional group to determine the mass of sediment per unit volume of bank and bed material with an intermediate grain diameter (b axis of clast) less than 2 mm. Most sediment likely to be transported within the Lake Tahoe basin is finer than 2 mm (Hunter, Mullen, and Simpson, 1988).

Bank samples were collected by driving metal cans horizontally into the banks until the cans were completely filled with material. Attempts were made to minimize compaction of samples, but occasionally sampling had to be repeated several times before a reasonably undisturbed sample was obtained.

Bulk density of each sample was determined by oven drying the sample at about 65 °C for 24 hours, weighing the sample, and dividing the mass by the volume of the sample-collection can. Samples were placed on a 2-mm sieve and mechanically shaken for 10-20 minutes. The percentage of sample finer than 2 mm was determined by dividing the mass of sediment passing through the 2-mm sieve by the mass of the total sample. The percentage of organic material was not determined.

When conditions permitted, bed samples were collected and processed in the same manner as bank samples, but often this was impossible because of large particle sizes and low cohesion of bed material. Under these conditions, bed-material bulk density was determined by scooping a small depression in exposed bed material, lining the depression with plastic sheeting, and filling the depression with water. The volume of added water was measured to give the volume of material excavated from the depression. The excavated material was placed in a plastic bucket and weighed with a spring scale. Bulk density (wet) then was calculated as the mass of excavated material divided by the volume of the excavated depression. This method was not entirely satisfactory because volume determinations were somewhat subjective and because samples were not dried prior to weighing. For remote sites with coarse bed material, however, this seemed to be the only practical method. Excavated material was wet-sieved in the field to determine the percentage of bed sediment finer than 2 mm.

## ASSUMPTIONS AND SOURCES OF ERRORS

The suspended-sediment budgets developed for the studied Lake Tahoe tributaries are subject to a number of assumptions and errors. Some error is introduced by developing sediment budgets for sediment finer than 2 mm and using measured suspended-sediment discharge for the sediment output components of the budgets rather than computing total sediment discharge. Suspended-sediment discharge is computed by multiplying the concentration of a depth-integrated sediment sample by the streamflow at the time of sampling. Suspended-sediment sampling equipment, however, samples only from the water surface down to 0.09 m above the channel bed; below this depth, sediment may travel either in suspension, in which case it is termed unsampled sediment, or as bedload. Transport of sediment in the silt and clay fractions (less than 0.062 mm) generally is adequately represented by suspended-sediment discharge because the small settling velocities of these fine particles result in concentrations that are uniform with depth in turbulent flow (Richards, 1982). For the sand (0.062

to 2 mm) fraction, concentrations may be nonuniform with depth, and bedload transport may be important; if the sand concentration is highest near the streambed or if a significant part of the sand load travels as bedload, suspended-sediment samples may underestimate the actual discharge of sand-size sediment. In such cases, the true discharge of sediment finer than 2 mm will equal the sum of the suspended load, the sand fraction of the bedload, and the difference between the measured concentration of suspended sand and the sand concentration of the unsampled sediment, multiplied by streamflow in the unsampled zone and a conversion factor (Hubbell, 1964, p. 7-9).

In most cases, determination of the unsampled sand discharge is not possible because computed sediment loads either underestimate or overestimate the true sediment loads (Hubbell, 1964, p. 7-9). Unsampled sand discharge and bedload transport of sand in the four studied Lake Tahoe tributaries probably result in an underestimation of sediment discharge from the study basins. On the basis of limited bedload data collected in Blackwood and Logan House Creeks (Hunter, Mullen, Simpson, and Grillo, 1987; unpublished data in files of U.S. Geological Survey), it is unlikely that suspended-sediment discharge is underestimated by more than 5 or 10 percent. Sand-sized sediment does not seem to constitute more than 5 to 10 percent of total sediment transport. This would represent an upper limit of error caused by lack of suspended-sediment data near the streambed.

Another sampling error results from comminution of sediment particles larger than 2 mm during transport (Dietrich and Dunne, 1978). Due to the crystalline nature of bedrock in the study basins, this error probably is not large; we have, however, no method of estimating its magnitude. Error due to comminution of large (greater than 2 mm) particles results in an underestimation of sediment mobilization or input. This error therefore tends to compensate for the error due to unmeasured sand discharge.

The rate of hillslope erosion measured at erosion boxes was assumed to equal the rate at which sediment was delivered from hillslopes to stream channels. The actual delivery of sediment to the channel system, however, may have been less than the estimated hillslope-erosion rate because some sediment was undoubtedly deposited along hillslopes. Hillslope-sediment erosion estimated for the suspended-sediment budgets therefore should be considered a maximum.

Calculations of sediment input and storage depend heavily on extrapolation and averaging of measurements obtained at monitoring sites. Such extrapolation was necessary due to the impracticality of sampling at all locations. Some inaccuracies probably result from this process; however, we attempted to minimize such inaccuracies by averaging measurements only within observably similar areas of the study basins.

## APPLICATION OF METHODS TO STUDY BASINS

For all four of the study basins, field methods were consistent and results of field measurements are comparable. The extent of monitoring, however, varied among basins, and the manner in which field measurements were applied to develop the sediment budgets for each basin differed to account for differences in the intensity of monitoring. Suspended-sediment budget results are considered most reliable for the basins with the most extensive monitoring, the Blackwood and Edgewood Creek basins, and less reliable for the General and Logan House Creek basins. Application of sediment-budget techniques to the individual basins is described in detail in the following sections; suspended-sediment budget calculation procedures are summarized in table 3.

### BLACKWOOD CREEK

Monitoring of hillslope-erosional processes was particularly intensive in the Blackwood Creek basin. Field observations indicated that variations in hillslope topography, vegetative cover, and aspect might cause variations in hillslope-erosional processes. Determination of sediment sources was complicated by the large size of the basin, heterogeneous geology, and numerous small tributary channels. A schematic representation of the suspended-sediment budget for the Blackwood Creek basin is presented in figure 7.

#### Hillslopes

Rates of hillslope erosion were determined from erosion-box-monitoring data. These rates are expressed in units of sediment mass per unit width of hillslope, measured along hillslope contours. Each erosion box sampled a hillslope width of only 0.3 m. To extrapolate these results to entire hillslopes, the erosion-box sites (fig. 2) were classed into four categories on the basis of aspect and cover (table 4).

**Table 3.** Calculation procedures to develop suspended-sediment budgets for the four study basins

[mm, millimeter; do., Do., ditto]

| Basin | Hillslopes | Sediment production from | | | |
|---|---|---|---|---|---|
| | | Tributary channels | | Main channel | |
| | | Streambanks | Streambed | Streambanks | Streambed |
| Blackwood Creek | Hillslope-sediment rate (4 aspect/ cover classes) × length of active streambank × percentage of hillslope sediment finer than 2 mm | Average bank-erosion rate (1st or 2d order) × estimated length of eroding banks × bulk density × percentage of sediment finer than 2 mm | Average bed-scour rate (1st or 2d order) × channel length × bulk density × percentage of sediment finer than 2 mm | Average bank-erosion rate (2 groups) × measured length of eroding bank × bulk density × percentage of sediment finer than 2 mm | Composite reach scour/fill rate × channel length × bulk density × percentage of sediment finer than 2 mm |
| General Creek | Not determined | Not determined | Not determined | do. | Do. |
| Edgewood Creek | Hillslope-sediment rate (1 aspect/ cover class) × length of active streambank × percentage of hillslope sediment finer than 2 mm | Not determined | Not determined | Average bank-erosion rate × estimated length of eroding bank × bulk density × percentage of sediment finer than 2 mm | Do. |
| Logan House Creek | Hillslope-sediment rate from Edgewood Creek × length of active streambank × percentage of hillslope sediment finer than 2 mm | Not determined | Not determined | do. | Do. |

Hillslope-erosion rates were averaged for each of the four aspect/cover categories (table 4). There were problems with erosion-box design and vandalism during 1984, 1985, and 1986. Data for only 1987 and 1988 were used and provided an average annual rate of hillslope erosion at each erosion-box site.

Areas containing each of the four aspect/cover categories were delineated on 1:24,000-scale topographic maps. Active stream channels were identified from aerial photographs and field observations and are assumed to be channels that carry water for at least part of each year. Interpretations of ground cover were made using aerial photographs. The lengths of active-channel streambank in each category, for areas contributory to each of the nine main-channel composite reaches, were measured with a map wheel, and these lengths were totaled. Left and right banks were measured separately. Annual hillslope-sediment production was computed as the average hillslope-erosion rate for each aspect/cover category multiplied by the length of active streambank within each category.

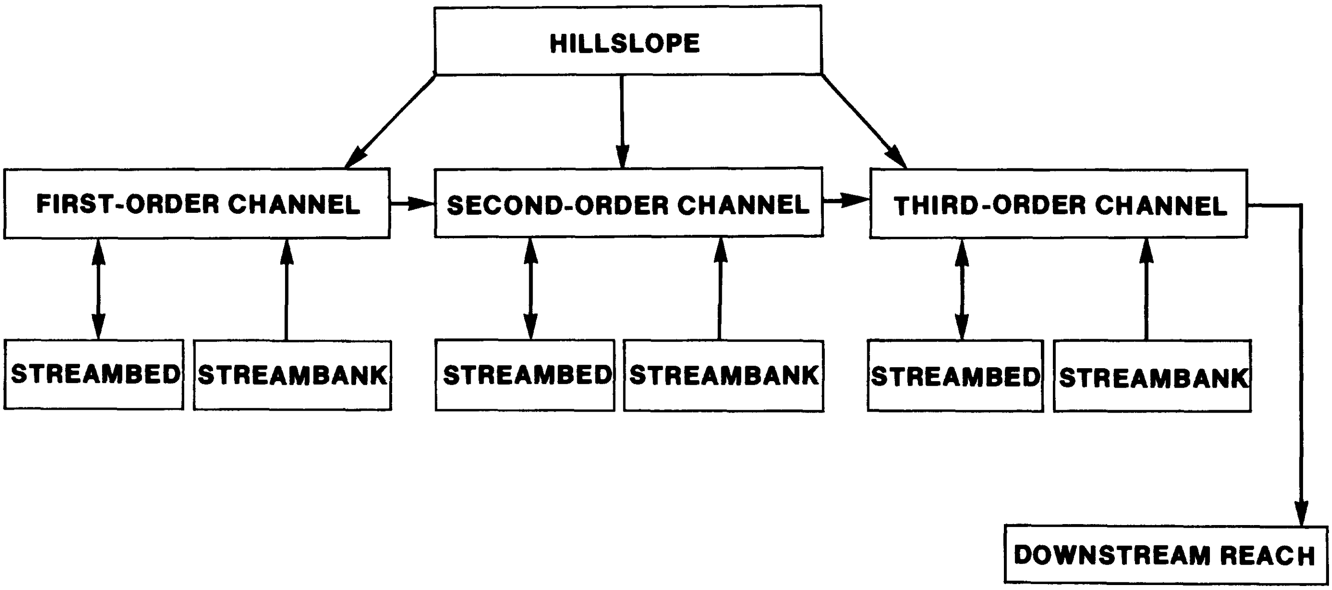

**Figure 7.** Schematic representation of suspended-sediment budget for the Blackwood Creek basin.

As an example, computations of estimated sediment production from Blackwood Creek hillslopes for R1 (fig. 2) are presented here, using data from table 4. Low-order tributaries to R1 flow along the bases of hillslopes in all four aspect-cover categories: north aspect with bare ground, north aspect with vegetative cover, south aspect with bare ground, and south aspect with vegetative cover. The hillslope-erosion rates determined for these categories are 0.068, 0.281, 2.08, and 3.92 (Mg/km)/a, respectively, and the total (left bank plus right bank) lengths of active streambank adjacent to hillslopes in these categories are 0.12, 14.1, 5.30, and 5.30 km, respectively. Sediment production for hillslopes with north aspect, bare ground is calculated as the product of the appropriate hillslope-transport rate, 0.068 (Mg/km)/a, and the bank length of channels adjacent to north aspect, bare ground, 0.12 km. Hillslope-sediment production from north aspect, bare ground is therefore estimated as 0.0082 Mg/a for hillslopes tributary to R1. Sediment production from the other three aspect-cover categories is calculated in the same manner. Total hillslope-sediment production for R1 is the sum of all four categories or 35.8 Mg/a.

### Tributaries

Erosion and deposition could not be measured on all the numerous tributary channels in the Blackwood Creek basin. Data therefore were collected at representative sample sites and averaged to obtain rates that could be applied to the entire active-channel system. To make the application of average rates as reasonable as possible, tributaries in the contributory areas for each of the nine main-channel composite reaches were classed as either first- or second-order channels. For purposes of analysis, a short section of third-order channel flowing into a main-channel composite reach of Blackwood Creek was included with second-order channels. The main channel is the highest order stream and receives first-, second-, and third-order tributaries. Channels with no tributaries are classed as first order, channels with only first-order tributaries are second order, and channels with first- and second-order tributaries are third order (Langbein and Iseri, 1960, p. 19).

Average rates of streambank erosion and streambed scour were determined from measurements at monumented cross sections on tributary channels

**Table 4.** Estimated average annual sediment production from hillslopes by aspect/cover category, Blackwood Creek, 1984-87

[Hillslope-transport rate and hillslope-sediment production include only transport of material finer than 2 millimeters; hillslope-transport rate is average of data from erosion boxes, 1987-88. km, kilometer; (Mg/km)/a, megagram per kilometer per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 2) | Length of active streambank (km) | Hillslope-transport rate [(Mg/km)/a] | Hillslope-sediment production (Mg/a) | Length of active streambank (km) | Hillslope-transport rate [(Mg/km)/a] | Hillslope-sediment production (Mg/a) |
|---|---|---|---|---|---|---|
| | **North/Bare** | | | **North/Vegetated** | | |
| R1 | 0.12 | 0.068 | 0.0082 | 14.1 | 0.281 | 3.97 |
| R2 | 0 | .068 | 0 | 4.57 | .281 | 1.28 |
| R3 | 0 | .068 | 0 | 1.22 | .281 | .34 |
| R4 | 0 | .068 | 0 | .73 | .281 | .21 |
| R5 | 0 | .068 | 0 | 0 | .281 | 0 |
| R6 | 0 | .068 | 0 | 5.42 | .281 | 1.52 |
| R7 | 0 | .068 | 0 | 0 | .281 | 0 |
| R8 | 0 | .068 | 0 | 0 | .281 | 0 |
| R9 | 0 | .068 | 0 | 0 | .281 | 0 |
| Total ..... | 0.12 | -- | 0.0082 | 26.0 | -- | 7.32 |
| | **South/Bare** | | | **South/Vegetated** | | |
| R1 | 5.30 | 2.08 | 11.0 | 5.30 | 3.92 | 20.8 |
| R2 | 0 | 2.08 | 0 | 2.99 | 3.92 | 11.7 |
| R3 | .12 | 2.08 | .250 | 2.26 | 3.92 | 8.86 |
| R4 | 0 | 2.08 | 0 | 2.25 | 3.92 | 8.82 |
| R5 | 0 | 2.08 | 0 | 2.01 | 3.92 | 7.88 |
| R6 | 2.19 | 2.08 | 4.56 | 6.28 | 3.92 | 24.6 |
| R7 | 0 | 2.08 | 0 | 0 | 3.92 | 0 |
| R8 | 0 | 2.08 | 0 | 0 | 3.92 | 0 |
| R9 | 0 | 2.08 | 0 | 0 | 3.92 | 0 |
| Total ..... | 7.61 | -- | 15.9 | 21.1 | -- | 82.6 |

(streambed scour was more significant than streambed fill in first- and second-order channels). Cross-section locations and yearly data are given by Hill and others (1990). Measurements showing erosion from tributary cross sections were used to determine average rates of bank erosion and bed scour in tributary channels (table 5).

Average area per unit length of eroding banks and streambeds was computed by dividing the measured area of eroding banks and streambed in the inventoried reaches by the length of the inventoried reach. This average area was computed for all first-order streams using data from first-order tributary reaches and for all second-order streams using data from

**Table 5.** Estimated average annual sediment production from tributary channels, Blackwood Creek basin, 1984-87

[Volume of eroded bank material converted to load using a bulk density of bank material finer than 2 millimeters, 0.61 megagram per cubic meter; volume of eroded or deposited bed material converted to load using a bulk density of bed material finer than 2 millimeters, 0.18 megagram per cubic meter. km, kilometer; $m^2$/km, square meter per kilometer; $m^2$, square meter; m/a, meter per annum; Mg/a, megagram per annum; nd, not determined]

| Composite reach (fig. 2) | Length of tributary channels (km) | Unit area ($m^2$/km) |  | Total area ($m^2$) |  | Bank-erosion rate (m/a) | Bed-scour rate (m/a) | Contributions to load (Mg/a) |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Streambanks | Streambed | Streambanks | Streambed |  |  | Banks | Bed |
| **First-order tributaries** |  |  |  |  |  |  |  |  |  |
| R1 | 10.9 | 421 | 3,360 | 4,590 | 36,600 | 0.021 | 0.009 | 58.8 | 59.0 |
| R2 | 4.57 | 421 | 3,360 | 1,920 | 15,400 | .021 | .009 | 24.6 | 25.0 |
| R3 | 3.23 | 421 | 3,360 | 1,360 | 10,900 | .021 | .009 | 17.4 | 17.6 |
| R4 | 1.46 | 421 | 3,360 | 615 | 4,910 | .021 | .009 | 7.9 | 7.9 |
| R5 | 2.01 | 421 | 3,360 | 846 | 6,750 | .021 | .009 | 10.9 | 11.0 |
| R6 | 9.51 | 421 | 3,360 | 4,000 | 32,000 | .021 | .009 | 51.2 | 51.8 |
| R7 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| R8 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| R9 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| **Second-order tributaries** |  |  |  |  |  |  |  |  |  |
| R1 | 8.72 | 252 | 3,140 | 2,200 | 27,400 | 0.091 | 0.0134 | 122 | 66.1 |
| R2 | 2.99 | 1,250 | 6,250 | 3,740 | 18,700 | .091 | .0134 | 208 | 45.1 |
| R3 | .49 | 1,250 | 6,250 | 613 | 3,060 | .091 | .0134 | 34.0 | 7.4 |
| R4 | 1.52 | 216 | 3,380 | 328 | 4,910 | .091 | .0134 | 18.2 | 11.8 |
| R5 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| R6 | 4.27 | 361 | 2,670 | 1,540 | 11,400 | .091 | .0134 | 85.5 | 27.5 |
| R7 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| R8 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |
| R9 | 0 | nd | nd | 0 | 0 | nd | nd | 0 | 0 |

second-order reaches. Locations of mapped tributary reaches and data for each reach are given by Hill and others (1990). Four different averages were computed for second-order eroding banks and streambeds in different parts of the basin (table 5) to reflect the diversity in channel types. Data from tributary reaches T1-T4 (fig. 2) were used. The appropriate average area per unit length of eroding banks and streambed was multiplied by the total length of each tributary channel, as measured on 1:24,000-scale topographic maps, to obtain estimates of the total area of eroding banks and streambed in each tributary channel.

The average bulk density and percentage of sediment finer than 2 mm were determined for tributary bank and bed material samples collected at tributary cross sections. These averages were used for all tributary channels.

The estimated area of eroding banks and streambed in first-order channels was multiplied by the average rate of bank retreat and bed scour to obtain the volume of sediment eroded from first-order channels in the contributory area for each main-channel composite reach. Sediment load was calculated by multiplying these volumes by the average values for bulk density and percentage finer than 2 mm and represents the input of sediment from erosion of first-order channels. For the routed suspended-sediment budget, this sediment load is assumed to be routed downstream to either a second-order channel or a main-channel composite reach. Sediment input from second-order channels was computed in a similar fashion.

### Main Channel

Computations of main-channel sediment input, output, and change in storage were made using data obtained from cross-sectional surveys, channel inventories, and sampling of streambank and streambed material. Computations were similar in most respects to those described previously for tributaries, but because more data for the main channel were available, less extrapolation was required. Main-channel composite reaches were defined as the length of channel measured from each cross-sectional group, extending halfway upstream and halfway downstream to adjacent cross-sectional groups; cross-section locations and yearly data are given by Hill and others (1990). Main-channel composite reaches at the upstream and downstream ends of the main channel ended at the farthest upstream and downstream cross-sectional groups, respectively, and extended in only one direction toward adjacent cross-sectional groups. The entire main channel of Blackwood Creek was inventoried, and the areas of eroding or stable streambanks and streambed area were estimated. Locations of inventoried reaches and inventory data were published by Hill and others (1990).

Rates of bank erosion were determined by grouping the average yearly rates of bank change at monumented cross sections into eroding (positive) rates and stable/aggrading (zero) rates. Data from left and right banks were combined. As previously noted, a value of zero was assigned for the stable/aggrading group on the basis of field observations that apparent aggradation was due primarily to vegetative growth and was not indicative of an actual increase in sediment storage. All banks not noted to be eroding were therefore considered stable, undergoing neither erosion nor aggradation. The rates for eroding banks were divided into two sets: cross sections 50-94, for the upstream reaches of the main channel (R1-R4), and cross sections 94.3-135, for the downstream channel reaches (R5-R9) (fig. 2).

The rate of streambed scour and fill for each cross section was determined using average yearly bed change. These rates were applied to main-channel reaches where cross-sectional groups were located (fig. 2) because the condition of the bed (eroding or stable/aggrading) could not be estimated during channel inventories.

Determinations of bulk density and percentage of bank and bed material finer than 2 mm were made for each cross-sectional group; the product of these measurements (equivalent to mass of sampled sediment finer than 2 mm) did not vary greatly among cross-sectional groups. The averages of the products of bulk density and percentage of material finer than 2 mm were used in calculations for all main-channel composite reaches. A decrease in bulk density in the downstream direction was offset by an increase in the percentage of sediment finer than 2 mm. Data are given by Hill and others (1990).

The areas of eroding banks and streambeds were multiplied by the appropriate rates for bank erosion and bed scour or fill to obtain the change in volume of sediment storage in each main-channel composite reach. Positive values indicate erosion; negative values indicate deposition. These volumes were multiplied by the average of bank and bed bulk density and percentage of sediment finer than 2 mm to obtain changes in storage in mass units. Changes in streambank and streambed storage were totaled for each main-channel composite reach. Estimated average annual channel-sediment production is given in table 6.

## GENERAL CREEK

Erosion rates in upland areas of the General Creek basin (fig. 3) are apparently very low because the area was scoured by glacial activity. For this reason, only the main channel in the basin was inventoried. Hillslopes mostly are composed of unweathered granitic bedrock, and tributary streams are few and generally characterized by bedrock and boulder channels. Large volumes of sediment, however, are stored along lower reaches of the main channel in the low-gradient glaciofluvial deposits forming the valley floor.

Main-channel composite reaches were selected with the criteria described previously for Blackwood Creek. The nine main-channel composite reaches,

**Table 6.** Estimated average annual sediment production, main channel Blackwood Creek, 1984-87

[Positive rate or load indicates erosion, negative rate or load indicates deposition; volume of eroded bank material converted to load using a bulk density of bank material finer than 2 millimeters, 0.72 megagram per cubic meter; volume of eroded or deposited bed material converted to load using a bulk density of bed material finer than 2 millimeters, 0.30 megagram per cubic meter. $m^2$, square meter; m/a, meter per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 2) | Streambanks | | | Streambed | | |
|---|---|---|---|---|---|---|
| | Area ($m^2$) | Rate (m/a) | Load (Mg/a) | Area ($m^2$) | Rate (m/a) | Load (Mg/a) |
| R1 | 378 | 0.120 | 32.7 | 3,180 | 0.019 | 18.1 |
| R2 | 877 | .120 | 75.8 | 7,320 | -.015 | -32.9 |
| R3 | 1,460 | .120 | 126 | 11,100 | -.048 | -159.9 |
| R4 | 389 | .120 | 33.6 | 4,300 | .008 | 9.8 |
| R5 | 1,510 | .265 | 288 | 10,400 | -.041 | -128.3 |
| R6 | 1,030 | .265 | 197 | 9,340 | .106 | 297.0 |
| R7 | 613 | .265 | 117 | 11,300 | .033 | 112.0 |
| R8 | 708 | .265 | 135 | 6,350 | -.019 | -36.1 |
| R9 | 949 | .265 | 181 | 5,780 | .048 | 83.2 |
| Total ....... | -- | -- | 1,186.1 | -- | -- | 162.9 |

defined by the locations of cross-sectional groups, are shown in figure 3. The main channel of General Creek was inventoried from the gaging station to the location of cross sections 10 and 15, a distance of about 13 km (fig. 3).

Main-channel suspended-sediment input, output, and change in storage were computed using techniques and procedures described previously for Blackwood Creek. Locations of channel cross sections are shown in figure 3; inventoried reaches are shown in the report by Hill and others (1990). Sediment input from reaches upstream from cross section 10 was assumed to be negligible because of low channel gradients and the bedrock streambanks and streambed. Cross-sectional data, channel-inventory results, and bank- and bed-material data are presented by Hill and others (1990). Estimated average annual channel-sediment production is given in table 7.

## EDGEWOOD CREEK

### Hillslopes

Rates of hillslope erosion were estimated using erosion-box-monitoring data, as described for Blackwood Creek hillslopes. Locations of erosion boxes (fig. 4) were selected to represent variations in altitude and topography. Vegetative cover and bedrock geology are fairly uniform, so fewer boxes were used than for Blackwood Creek. Erosion-box data are given by Hill and others (1990). Separate rates for aspect-cover classes were not determined because of the small number of erosion boxes. Instead, average yearly rates for all erosion boxes for 1987-88 were applied to the total length of active-channel streambank.

Active-channel streambanks within contributory areas of the Edgewood Creek basin were identified for each main-channel composite reach from topographic maps and aerial photographs. Active channels were defined as channels that carry water during at least part of each year and are immediately adjacent to hillslopes. Relict ephemeral streams and streams bordered by low-gradient flood-plain meadows and thickets were excluded because direct hillslope contributions to such channels are unlikely. Estimated average annual sediment production from hillslopes is given in table 8.

### Channels

The Edgewood Creek basin is small and channels are of fairly uniform dimension. No distinction was made between the main channel and tributary

**Table 7.** Estimated average annual sediment production, main channel General Creek, 1984-87

[Positive rate or load indicates erosion, negative rate or load indicates deposition; volume of eroded bank material converted to load using a bulk density of bank material finer than 2 millimeters, 0.74 megagram per cubic meter; volume of eroded or deposited bed material converted to load using a bulk density of bed material equal to or finer than 2 millimeters, 0.48 megagram per cubic meter. $m^2$, square meter; m/a, meter per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 3) | Streambanks | | | Streambed | | |
|---|---|---|---|---|---|---|
| | Area ($m^2$) | Rate (m/a) | Load (Mg/a) | Area ($m^2$) | Rate (m/a) | Load (Mg/a) |
| R1 | 978 | 0.019 | 9.4 | 16,600 | 0.012 | 95.6 |
| R2 | 117 | .019 | 1.1 | 7,330 | .011 | 38.7 |
| R3 | 105 | .019 | 1.0 | 5,140 | -.011 | -27.1 |
| R4 | 177 | .019 | [1]0 | 7,370 | -.001 | -4.6 |
| R5 | 360 | .019 | [1]0 | 6,420 | -.006 | -16.9 |
| R6 | 254 | .019 | [1]0 | 4,550 | .006 | 12.7 |
| R7 | 553 | .110 | 25.8 | 6,050 | -.025 | -72.6 |
| R8 | 809 | .110 | 37.7 | 9,160 | .024 | 106 |
| R9 | 664 | .110 | 31 | 4,870 | -.001 | -2.3 |
| Total ....... | -- | -- | 106 | -- | -- | 130 |

[1] Bank erosion rate was within precision of measurement and was assumed to be zero.

**Table 8.** Estimated average annual sediment production from hillslopes, Edgewood Creek, 1984-87

[Hillslope-transport rate and hillslope-sediment production include only transport of material finer than 2 millimeters; hillslope-transport rate is average of data from erosion boxes, 1987-88. km, kilometer; (Mg/km)/a, megagram per kilometer per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 4) | Length of active streambank (km) | Hillslope-transport rate [(Mg/km)/a] | Hillslope-sediment production (Mg/a) |
|---|---|---|---|
| R1 | 0.74 | 0.30 | 0.2 |
| R2 | 3.30 | .30 | 1.0 |
| R3 | 2.44 | .30 | .7 |
| R4 | 1.82 | .30 | .6 |
| R5 | .48 | .30 | .1 |
| R6 | .86 | .30 | .3 |
| Total .... | 9.64 | -- | 2.9 |

channels as in the Blackwood Creek basin. Channel cross sections and inventories extended throughout the perennial reaches of the basin. Inventoried reaches were delimited by the locations of cross-sectional groups, as described previously for Blackwood Creek. Locations of cross sections are shown in figure 4. Cross-sectional data are presented by Hill and others (1990).

Within inventoried reaches, measured areas of eroding streambanks and streambed were extrapolated to entire channel lengths using the methods described for tributary channels in the Blackwood Creek basin. Inventoried reaches that were within each composite reach were used to estimate bank and bed area for that particular composite reach. The locations of composite reaches are shown in figure 4. Locations of inventoried reaches and channel inventory results are given by Hill and others (1990).

Procedures for determining changes in streambed scour and fill and rates of streambank erosion were the same as outlined for Blackwood Creek. Negative bank-erosion rates were assigned a value of zero, and all banks not classified as eroding were assumed to be

**Table 9.** Estimated average annual channel-sediment production, Edgewood Creek, 1984-87

[Positive rate or load indicates erosion, negative rate or load indicates deposition; volume of eroded bank material converted to load using a bulk density of bank material finer than 2 millimeters, 0.60 megagram per cubic meter; volume of eroded or deposited bed material converted to load using a bulk density of bed material equal to or finer than 2 millimeters, 0.87 megagram per cubic meter. km, kilometer; $m^2$/km, square meter per kilometer; $m^2$, square meter; m/a, meter per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 4) | Reach length (km) | Streambanks | | | | Streambed | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Unit area ($m^2$/km) | Total area ($m^2$) | Rate (m/a) | Load (Mg/a) | Unit area ($m^2$/km) | Total area ($m^2$) | Rate (m/a) | Load (Mg/a) |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| R1 | 0.79 | 324 | 256 | 0.022 | 3.4 | 1,290 | 1,020 | 0.016 | 14.2 |
| R2 | 1.71 | 353 | 604 | .022 | 8.0 | 1,320 | 2,260 | .009 | 17.7 |
| R3 | 1.58 | 273 | 431 | .022 | 5.7 | 1,570 | 2,480 | .006 | 12.9 |
| R4 | 1.71 | 354 | 605 | .022 | 8.0 | 1,080 | 1,850 | -.018 | -29.0 |
| R5 | .47 | 945 | 444 | .022 | 9.8 | 2,650 | 1,250 | -.012 | -13.1 |
| R6 | .51 | 767 | 390 | .022 | 8.6 | 1,870 | 950 | -.010 | -8.3 |
| Total ..... | 6.77 | -- | 2,730 | -- | 43.5 | -- | 9,810 | -- | -5.6 |

stable. The results of these computations are given by Hill and others (1990). Estimated average annual channel-sediment production is given in table 9.

### LOGAN HOUSE CREEK

Only channel processes were monitored in the Logan House Creek basin. Methods were identical to those described for Blackwood Creek. Locations of channel composite reaches and cross sections are shown in figure 5; cross-sectional data and channel-mapping locations and results are presented by Hill and others (1990). Composite reaches R6A and R6B were inventoried, but were not included in sediment-budget calculations because no flow was observed in these reaches during the study period. Properties of bank and bed samples also are given by Hill and others (1990). Because general geology and climate of the Logan House Creek basin are similar to those of the Edgewood Creek basin, hillslope-sediment production was estimated using the average hillslope-transport rate for Edgewood Creek and multiplying by the active-channel bank length as described for Edgewood Creek. Estimated average annual sediment production from hillslopes and channels is given in tables 10 and 11.

**Table 10.** Estimated average annual sediment production from hillslopes, Logan House Creek, 1984-87

[Hillslope-transport rate and hillslope-sediment production include only transport of material finer than 2 millimeters; hillslope transport rate is average of data from Edgewood Creek basin erosion boxes, 1987-88. Reaches R6A and R6B not included in sediment calculations. km, kilometer; (Mg/km)/a, megagram per kilometer per annum; Mg/a, megagram per annum; --, does not apply]

| Composite reach (fig. 5) | Length of active streambank (km) | Hillslope transport rate [(Mg/km)/a] | Hillslope sediment production (Mg/a) |
|---|---|---|---|
| R1 | 1.22 | 0.30 | 0.37 |
| R2 | .24 | .30 | .07 |
| R3 | .61 | .30 | .18 |
| R4 | 1.10 | .30 | .33 |
| R5 | 1.10 | .30 | .33 |
| R7 | .30 | .30 | .09 |
| Total ..... | 4.57 | -- | 1.37 |

**Table 11.** Estimated average annual channel-sediment production, Logan House Creek, 1984-87

[Positive rate or load indicates erosion, negative rate or load indicates deposition; volume of eroded bank material converted to load using a bulk density of bank material finer than 2 millimeters, 0.37 megagram per cubic meter; volume of eroded or deposited bed material converted to load using a bulk density of bed material equal to or finer than 2 millimeters, 0.56 megagram per cubic meter. Reaches R6A and R6B not included in sediment-budget calculations. km, kilometer; $m^2$/km, square meter per kilometer; $m^2$, square meter; m/a, meter per annum; Mg/a, megagram per annum; --, does not apply]

| | | Streambanks | | | | Streambed | | | |
|---|---|---|---|---|---|---|---|---|---|
| Composite reach (fig. 5) (1) | Reach length (km) (2) | Unit area ($m^2$/km) (3) | Total area ($m^2$) (4) | Rate (m/a) (5) | Load (Mg/a) (6) | Unit area ($m^2$/km) (7) | Total area ($m^2$) (8) | Rate (m/a) (9) | Load (Mg/a) (10) |
| R1 | 0.85 | 312 | 265 | 0.023 | 2.2 | 772 | 656 | -0.001 | -0.4 |
| R2 | .55 | 204 | 112 | .023 | 1.0 | 704 | 387 | -.031 | -6.7 |
| R3 | .61 | 249 | 152 | .023 | 1.3 | 969 | 591 | -.011 | -3.6 |
| R4 | .73 | 317 | 231 | .023 | 2.0 | 891 | 651 | .004 | 1.5 |
| R5 | .55 | 329 | 181 | .023 | 1.5 | 1,040 | 572 | -.010 | -3.2 |
| R7 | .20 | 417 | 83 | .023 | .7 | 1,010 | 202 | .002 | .2 |
| Total .... | 3.49 | -- | 1,020 | -- | 8.7 | -- | 3,060 | -- | -12.2 |

## SUSPENDED-SEDIMENT BUDGETS

### BLACKWOOD CREEK

Results of the Blackwood Creek suspended-sediment budget are presented in table 12. Estimates of hillslope erosion, the amount of sediment contributed by tributary channels, and estimates of main-channel-sediment erosion and deposition are given in tables 4, 5, and 6. Average annual suspended-sediment output predicted by the gross sediment budget is 2,420 Mg (table 12, col. 8). Because the routed sediment budget accounts for sediment deposition in the gravel-extraction pond, routed-sediment output (2,100 Mg/a, table 12, col. 9) was less than output predicted by the gross sediment budget. These predictions compare well to the average annual suspended-sediment discharge of 2,030 Mg measured between 1984 and 1987 (table 1). Of the 2,420 Mg/a of output estimated by the gross sediment budget (table 12), 106 Mg/a (4 percent) comes from hillslopes, 968 Mg/a (40 percent) from first-and second-order tributaries, 1,190 Mg/a (49 percent) from eroding banks along the main channel, and 163 Mg/a (7 percent) from the bed of the main channel. Sediment is stored temporarily along four of the nine composite reaches (table 12).

### GENERAL CREEK

Results of the General Creek suspended-sediment budgets are presented in table 13. Estimates of channel-sediment erosion and deposition are given in table 7. Sediment output predicted by the gross sediment budget equals output predicted by the routed sediment budget (table 13, cols. 5 and 6). As was the case in Blackwood Creek, the 236 Mg/a of sediment output (table 13) estimated from our sediment-budget calculations compares well with the average annual suspended-sediment discharge of 201 Mg measured at the General Creek gaging station 1033645 between 1984-87 (table 1). In General Creek basin (table 7), especially in the upper reaches, bank-erosion rates were low and were within the precision of measurement at three cross-sectional groups. Because there was little bank erosion, the storage and mobilization of sediment from the streambed is an important component of the sediment budget. Roughly equal amounts of sediment were released by bank erosion and bed scour. A net storage of sediment in the streambed occurred along four of the nine composite reaches (table 13).

During 1984-87, average-annual suspended-sediment yield from General Creek was 10.4 Mg/km$^2$, about one-seventh of the 67.9 Mg/km$^2$ yield from

**Table 12.** Estimated average annual suspended-sediment budget, Blackwood Creek, 1984-87

[All sediment data are in megagrams per annum. Positive loads indicate erosion; negative loads indicate deposition. Gross sediment budget (column 8) is the sum of hillslopes, tributaries, streambanks, and streambed. Routed sediment budget (column 9) is cumulative sum of gross sediment budget. Totals have been rounded. km, kilometer]

| Composite reach (fig. 2) | Reach length (km) | Sediment production from | | | | | Gross sediment budget | Routed sediment budget |
|---|---|---|---|---|---|---|---|---|
| | | Hillslopes | Tributaries | | Main channel | | | |
| | | | First order | Second order | Streambanks | Streambed | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| R1 | 0.417 | 35.8 | 118 | 188 | 32.7 | 18.1 | 393 | 393 |
| R2 | .721 | 13.0 | 49.6 | 253 | 75.8 | -32.9 | 358 | 751 |
| R3 | .819 | 9.4 | 35.0 | 41.4 | 126 | -160 | 51.8 | [1]482 |
| R4 | .395 | 9.0 | 15.8 | 30.0 | 33.6 | 9.8 | 98.2 | 580 |
| R5 | .942 | 7.9 | 21.9 | 0 | 288 | -128 | 190 | 770 |
| R6 | .862 | 30.7 | 103 | 113 | 197 | 297 | 741 | 1,510 |
| R7 | .743 | 0 | 0 | 0 | 117 | 112 | 229 | 1,740 |
| R8 | .777 | 0 | 0 | 0 | 135 | -36.1 | 99 | 1,840 |
| R9 | .645 | 0 | 0 | 0 | 181 | 83.2 | 264 | 2,100 |
| Total .... | 6.321 | 106 | 343 | 625 | 1,190 | 163 | 2,420 | 2,100 |

[1] Adjusted for gravel-extraction pond trap efficiency of 40 percent.

**Table 13.** Estimated average annual suspended-sediment budget, General Creek, 1984-87

[All sediment data are in megagrams per annum. Positive loads indicate erosion; negative loads indicate deposition. Gross sediment budget (column 5) is the sum of streambanks and streambed. Routed sediment budget (column 6) is cumulative sum of gross sediment budget. Totals have been rounded. km, kilometer]

| Composite reach (fig. 3) | Reach length (km) | Sediment production from | | Gross sediment budget | Routed sediment budget |
|---|---|---|---|---|---|
| | | Streambanks | Streambed | | |
| (1) | (2) | (3) | (4) | (5) | (6) |
| R1 | 3.07 | 9.4 | 95.6 | 105 | 105 |
| R2 | 1.35 | 1.1 | 38.7 | 39.8 | 145 |
| R3 | 1.10 | 1.0 | -27.1 | -26.1 | 119 |
| R4 | 1.24 | [1]0 | -4.6 | -4.6 | 114 |
| R5 | 1.10 | [1]0 | -16.9 | -16.9 | 97 |
| R6 | .95 | [1]0 | 12.7 | 12.7 | 110 |
| R7 | 1.42 | 25.8 | -72.6 | -46.8 | 63 |
| R8 | 1.76 | 37.7 | 106 | 144 | 207 |
| R9 | .80 | 31 | -2.3 | 28.7 | 236 |
| Total ........ | 12.8 | 106 | 130 | 236 | 236 |

[1] Bank erosion rate was within precision of measurement and was assumed to be zero.

Blackwood Creek (table 1). This results because there is virtually no input of sediment from tributaries in the long, narrow General Creek basin and because the area of eroding banks and the rates at which those banks are eroding (table 7) are much less than in the Blackwood Creek basin (tables 5 and 6).

## EDGEWOOD CREEK

Results of the Edgewood Creek sediment budget are presented in table 14. Estimates of hillslope-erosion and channel-sediment erosion and deposition are given in tables 8 and 9, respectively. The average annual suspended-sediment load estimated from both the gross and routed sediment budgets was 40.8 Mg (table 14, cols. 6 and 7), which compares well with the average suspended-sediment discharge measured during 1984-87 of 40.3 Mg (table 1). Most of the measured sediment discharge came from streambank erosion. Hillslopes contributed only 2.9 Mg/a of sediment to the channel, compared with 43.5 Mg/a from streambank erosion. The streambed was a net sink for sediment; deposition occurred in streambeds in three of the six composite reaches (table 14).

## LOGAN HOUSE CREEK

Results of the Logan House Creek sediment budget are presented in table 15. Estimates of hillslope erosion and channel-sediment erosion and deposition are given in tables 10 and 11. The average annual suspended-sediment load estimated from the routed sediment budget was 3.4 Mg (table 15, col. 7), compared with measured average annual suspended-sediment discharge of 3.8 Mg during 1984-87 (table 1). However, more sediment was stored in the channel than can be attributed to estimated hillslope-sediment erosion or channel erosion (table 15, col. 6). The routed sediment output (table 15, col. 7) approximates the measured sediment output (table 1) more closely than the estimated gross output (table 15, col. 6). The sediment "deficit" does not accumulate downstream in the routed sediment because sediment output of zero was assigned to composite reaches with net sediment storage (streambed storage greater than the sum of hillslope and bank erosion).

The discrepancy between results of the gross and routed sediment budgets (table 15, col. 6 and 7) indicates that we were unable to adequately measure

**Table 14.** Estimated average annual suspended-sediment budget, Edgewood Creek, 1984-87

[All sediment data are in megagrams per annum. Positive loads indicate erosion; negative loads indicate deposition. Gross sediment budget (column 6) is the sum of hillslopes, streambanks, and streambed. Routed sediment budget (column 7) is cumulative sum of gross sediment budget. Totals have been rounded. km, kilometer]

| Composite reach (fig. 4) | Reach length (km) | Sediment production from | | | Gross sediment budget | Routed sediment budget |
|---|---|---|---|---|---|---|
| | | Hillslopes | Streambanks | Streambed | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| R1 | 0.79 | 0.2 | 3.4 | 14.2 | 17.8 | 17.8 |
| R2 | 1.71 | 1.0 | 8.0 | 17.7 | 26.7 | 44.5 |
| R3 | 1.58 | .7 | 5.7 | 12.9 | 19.3 | 63.8 |
| R4 | 1.71 | .6 | 8.0 | -29.0 | -20.4 | 43.4 |
| R5 | .47 | .1 | 9.8 | -13.1 | -3.2 | 40.2 |
| R6 | .51 | .3 | 8.6 | -8.3 | .6 | 40.8 |
| Total ..... | 6.77 | 2.9 | 43.5 | -5.6 | 40.8 | 40.8 |

**Table 15.** Estimated average annual suspended-sediment budget, Logan House Creek, 1984-87

[All sediment data are in megagrams per annum. Positive loads indicate erosion, negative loads indicate deposition. Gross sediment budget (column 6) is the sum of hillslopes, streambanks, and streambed. Routed sediment budget (column 7) is cumulative sum of gross sediment budget but cannot be less than zero; output from reaches with net negative load is assumed to be zero. Reaches R6A and R6B not included in sediment budget calculations. km, kilometer]

| Composite reach (fig. 5) | Reach length (km) | Sediment production from | | | Gross sediment budget | Routed sediment budget |
|---|---|---|---|---|---|---|
| | | Hillslopes | Streambanks | Streambed | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| R1 | 0.85 | 0.37 | 2.2 | -0.4 | 2.2 | 2.2 |
| R2 | .55 | .07 | 1.0 | -6.7 | -5.6 | 0 |
| R3 | .61 | .18 | 1.3 | -3.6 | -2.1 | 0 |
| R4 | .73 | .33 | 2.0 | 1.5 | 3.8 | 3.8 |
| R5 | .55 | .33 | 1.5 | -3.2 | -1.4 | 2.4 |
| R7 | .20 | .09 | .7 | .2 | 1.0 | 3.4 |
| Total ..... | 3.49 | 1.37 | 8.7 | -12.2 | -2.1 | 3.4 |

all components of the Logan House Creek sediment budget. Quantification of erosional processes was especially difficult in the Logan House Creek basin because erosion rates are very low; thus, any errors in measurement of sediment input or storage will comprise a relatively large percentage of sediment output.

## BASIN AND CHANNEL CHARACTERISTICS AFFECTING SUSPENDED-SEDIMENT BUDGETS

Field monitoring associated with this study seems to have provided reasonable estimates of the rates at which dominant erosional processes are operating in the four study basins. Sediment discharge predicted from gross and routed sediment budget calculations closely matched measured sediment discharge, with the exception of the Logan House Creek basin, where sediment yields are very low (table 16).

Results of the sediment-budget study indicate that stream channels are by far the dominant source of sediment in the study basins (tables 12-15). This finding agrees with Hill and Nolan's (1990) conclusion that drainage density (length of channel per unit area of drainage basin) is the most important variable in controlling sediment-yield variations among Lake Tahoe tributaries.

### HILLSLOPE EROSION

Although hillslope erosion was a minor component of all four sediment budgets, some discussion of processes affecting hillslope erosion is warranted.

#### GEOLOGIC EFFECTS

One reason that sediment budgets for the Blackwood Creek and General Creek basins include little or no sediment from hillslopes is that glaciation in those basins produced wide, U-shaped valleys that now contain the main channels of those streams. These main-channel streams are separated from hillslopes by wide, flat valley floors. Weathered regolith was removed and there is, therefore, little opportunity for sediment mobilized from hillslopes to enter main channels in these two basins. Hillslopes and stream channels are effectively decoupled throughout most of these basins, at least during the time frame of the study.

Rock units in the study basins do not seem to be particularly susceptible to abundant landslide activity. Field inventories and mapping from aerial photographs indicate that less than 0.1 percent of the area in any of the four study basins is characterized by active landslides (Hill and others, 1990). Landslides

**Table 16.** Gross sediment budgets for four study basins, 1984-87

[All data are in megagrams per annum of material finer than 2 millimeters. Net sediment mobilized is sum of sediment production from all sources and changes in sediment storage. Positive loads indicate erosion; negative loads indicate deposition. --, not determined]

| Basin | Sediment production from | | | | | Net sediment mobilized | Measured average annual suspended-sediment discharge (table 1) |
|---|---|---|---|---|---|---|---|
| | Hillslopes | Tributary channels | | Main channel | | | |
| | | Stream-banks | Stream-bed | Stream-banks | Stream-bed | | |
| Blackwood Creek ..... | 106 | 638 | 330 | 1,190 | 163 | 2,420 | 2,030 |
| General Creek ....... | -- | -- | -- | 106 | 130 | 236 | 201 |
| Edgewood Creek ..... | 2.9 | -- | -- | 43.5 | -5.6 | 40.8 | 40.3 |
| Logan House Creek ... | 1.37 | -- | -- | 8.7 | -12.2 | -2.1 | 3.8 |

therefore are only a minor source of hillslope sediment. No landslide activity was observed in the study basins during 1984-87.

Several other characteristics found in the study basins may affect sediment yield from hillslopes. The metamorphic and volcanic rocks underlying the Blackwood Creek basin produce thin soils that support only sparse vegetation. These sparsely vegetated slopes seem susceptible to erosion by sheetwash and rill erosion and may increase runoff from the basin. The sandy soils formed by decomposition of granite in the Edgewood and Logan House Creek basins are highly permeable and, under natural conditions, are not particularly susceptible to sheetwash and rill erosion.

### EFFECTS OF RODENT ACTIVITY

At several hillslope-erosion monitoring sites in the Blackwood and Edgewood Creek basins (figs. 2 and 4), burrowing animals had disrupted large amounts of surface material. Such activity seems to have a substantial influence on hillslope erosion. Most rodent burrowing in the Lake Tahoe basin probably is that of pocket gophers (*Thomomys* spp.). To provide an indication of the effects of burrowing animals on the rate of hillslope erosion, apparent rodent activity was recorded within a 1-m radius of each erosion box during field visits in 1988. The hillslope-erosion-rate results for 1988 then were classified as either affected by rodents or not. Results for these two groups are significantly different ($p$=0.05), and the average of the rodent-affected sites is 35 times higher than the average of sites not affected. In the absence of any measure of rodent population in the study basins, neither the extent of rodent activity nor their overall basinwide effect on sediment-transport processes can be precisely determined. Results of studies in other areas (Grinnell, 1923; Ellison, 1946; Thorn, 1978), however, indicate that displacement of soil by rodents could represent a major process of hillslope erosion in these four Lake Tahoe study basins.

Several studies in the Sierra Nevada and Rocky Mountains have documented rates of soil erosion and volumes of excavation by pocket gophers. On the basis of field observations in Yosemite National Park, Grinnell (1923) estimated that pocket gophers brought to the land surface an average of 890 (Mg/km$^2$)/a of soil in areas inhabited by gophers, or 2.52 (Mg/km$^2$)/a over the entire park. Ellison (1946) measured an annual rate of 1,120 (Mg/km$^2$)/a in the Wasatch Mountains of Utah. Ellison (1946) considered that 3.5 percent of the area he studied was affected by gophers, and so the overall rate for the area is about 39 (Mg/km$^2$)/a. Thorn (1978) estimated a rate of 3,900 to 5,800 (Mg/km$^2$)/a in the Rocky Mountains of Colorado. These rates refer only to soil displaced from the subsurface to the surface and do not indicate the amount of material mobilized from the site and discharged from the drainage basin. Ellison (1946), however, noted that gopher workings commonly were cast into gullies and were transported from the site.

Variability in rodent-related displacement rates is due partly to the variable distribution of rodents. Previous studies have indicated that gophers preferentially inhabit meadows (Grinnell, 1923; Linsdale, 1938; Ingles, 1952; Klikoff, 1965). In the Blackwood Creek basin, evidence of gophers is most common near the margins of meadows and on hillslopes that have herbaceous or shrubby vegetation. Gopher activity was only occasionally apparent in forested areas. Where soils were thin or lacking and vegetation sparse or absent, gopher activity was not noted. In the absence of quantitative data on gophers in the Lake Tahoe area, it seems reasonable to apply Grinnell's (1923) excavation rate of 2.52 (Mg/km$^2$)/a in estimating gopher activity. In the Blackwood Creek basin, for example, this rate would result in a total of 75 Mg/a of soil disruption. If all this material moved downslope and into stream channels, gophers could account for as much as 71 percent of the average annual hillslope erosion estimated for the Blackwood Creek basin (table 4). A similar result was reported by Imerson (1976), who observed during his study of forested area in Luxembourg, that most of the downslope sediment transport was due to the actions of burrowing animals.

## CHANNEL EROSION

In addition to the general finding that stream channels are the dominant source of sediment, the sediment-budget study indicates that types and rates of channel erosion differ among the drainage basins. Large differences exist in the amount of sediment coming from individual basins, as well as in the source of that sediment. Erosion data for all four study basins are summarized in figure 8. For example, more than 70 percent of the sediment mobilized in the General Creek basin came from streambed erosion, whereas nearly 80 percent of the sediment mobilized in the Logan House Creek basin came from streambank erosion (fig. 8). Data shown in figure 8 represent the total amount of sediment mobilized in each basin. Some of that sediment was redeposited along streambeds in some basins.

Because channels in the study basins are formed primarily in alluvium, channel morphology is a function of the amount and nature of transportable sediment, streamflow, and the character of material making up the stream channel (Leopold and others, 1964, p. 198). Although ways in which these variables can interact to form channels in any one drainage basin can be complex, the following discussion presents a few interactions indicated by the sediment-budget data.

### EFFECTS OF CHANNEL CHARACTERISTICS

Many of the differences in sediment budgets for the four study basins can be attributed to differences in streambank-erosion rates, channel size, and characteristics of sediment found in streambanks and streambeds. For example, when normalized by drainage area, nearly 13 times more sediment was mobilized by streambank erosion in the Blackwood Creek basin than in the General Creek basin (fig. 9). One reason for this large difference is that the channels in most of the upstream part of the General Creek basin are formed in granitic bedrock or are buttressed by large granite boulders. Rates of streambank erosion in the Edgewood and Logan House Creek basins also were significantly less than the rates of streambank erosion in the Blackwood Creek basin. Streambanks along the relatively small channels of the Edgewood and Logan House Creek basins are effectively buttressed in many locations by dense growths of willow and alder and apparently are able to resist erosive forces (fig. 10).

Investigations in other localities indicate that riparian vegetation can effectively reduce bank erosion rates. For example, Hadley (1961) found that the establishment of tamarisk was sufficient to stabilize eroding streambanks along a channel reach in Arizona. A more recent study in the Colorado Plateau (Graf, 1978) reported that tamarisk stabilized streambanks and decreased channel width between 13 and 55 percent. Experimental evidence from braided streams in Alberta, Canada (Smith, 1976), indicated that root mats of 50-mm thickness can increase the resistance to erosion of fine-grained bank material by a factor of 20,000.

The work of Zimmerman and others (1967) supports the finding that vegetation has a greater effect on bank erosion along the smaller Edgewood and Logan House Creek channels than along the larger Blackwood and General Creek channels. Zimmerman

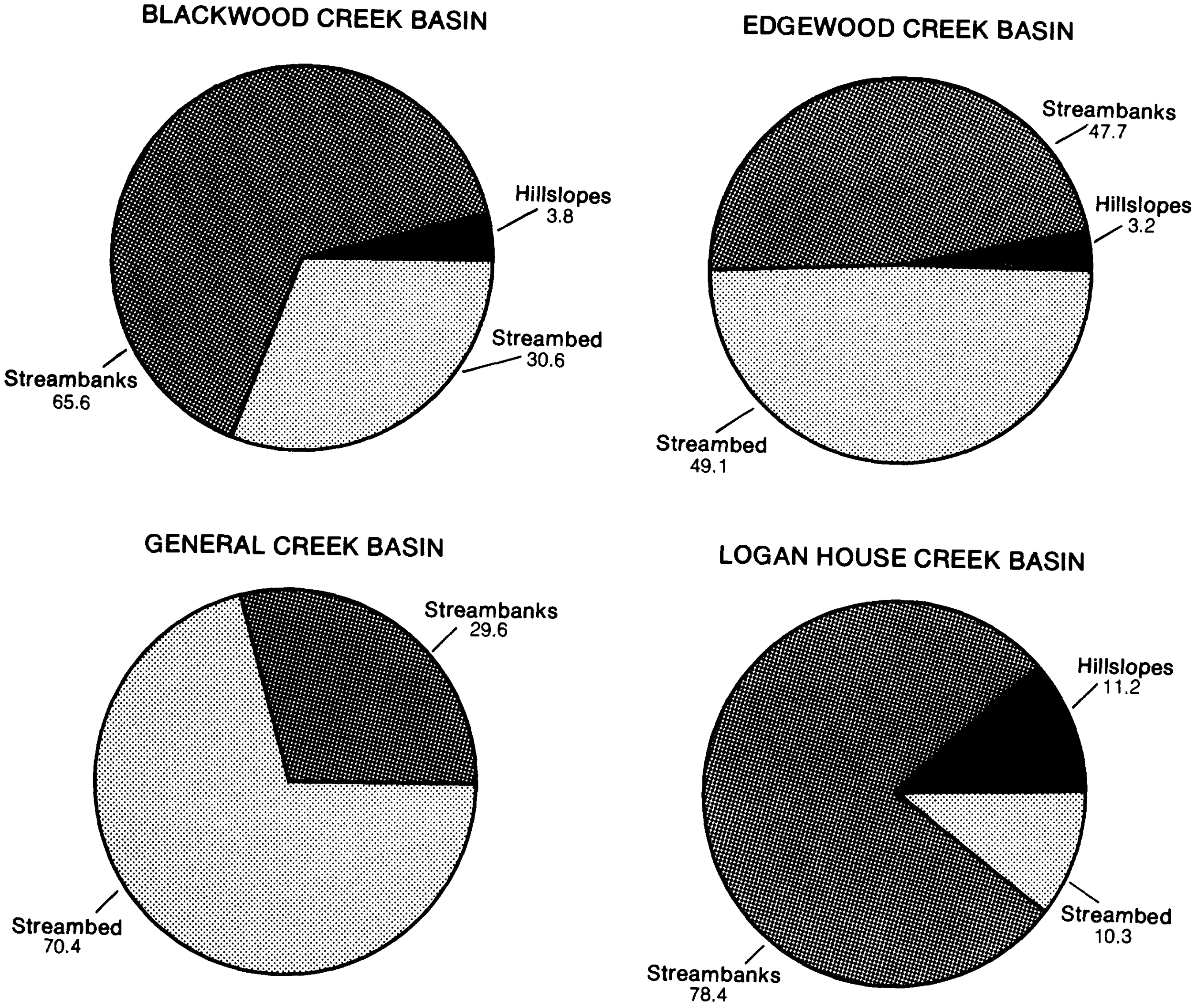

**Figure 8.** Percentage of sediment mobilized by hillslope, streambank, and streambed erosion.

and others (1967) found that channel reaches with small drainage areas, such as Edgewood and Logan House Creeks, were affected more by vegetation than were reaches with larger drainage areas (similar to Blackwood and General Creeks). The main channels of the larger and wetter westside basins of Blackwood and General Creeks are too deep to be stabilized by riparian thickets of willow and alder. Bank heights along these channels are often in excess of 2 m, and roots of most riparian species penetrate only a meter or less. Bank heights in Edgewood and Logan House Creeks rarely exceed 1 m.

Despite the similarity of Edgewood and Logan House Creeks in area of eroding bank per unit of drainage area and bank-erosion rate, the average annual suspended-sediment yield from Edgewood Creek is roughly seven times that of Logan House Creek (table 1). In Logan House Creek, more sediment was stored along the streambed than was mobilized from streambanks or hillslopes. Approximately 5 times more sediment was eroded from streambanks and roughly 25 times more sediment was eroded from streambeds in Edgewood Creek than in Logan House Creek (positive values

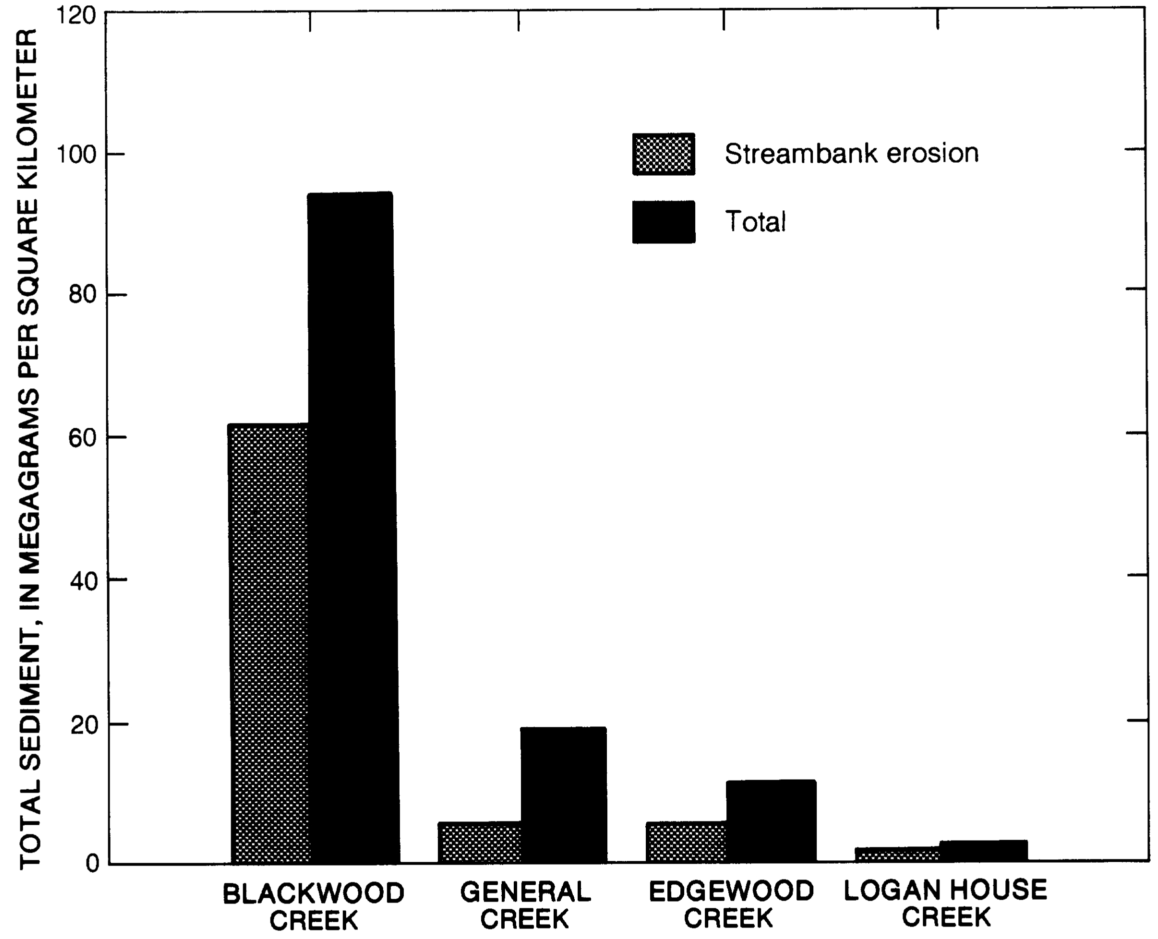

**Figure 9.** Total sediment finer than 2 millimeters, normalized by drainage area, mobilized by all processes and by streambank erosion.

tables 9 and 11, cols. 6 and 10). Data in tables 9 and 11 indicate that the substantially larger amount of sediment eroded from streambanks in Edgewood Creek resulted from a combination of factors: (1) greater length of active channel in the Edgewood Creek basin; (2) greater area of eroding bank per unit length of channel in Edgewood Creek; (3) bulk density and percentage of eroded bank material finer than 2 mm are considerably greater in Edgewood Creek; and (4) streambed sediment in Edgewood Creek is abundant and easily transported.

### EFFECTS OF STREAMFLOW

Hill and Nolan (1990) suggested that while drainage density is the most important variable, average annual precipitation is the second most important variable in controlling sediment discharge from Lake Tahoe tributary basins. A positive correlation of sediment discharge with precipitation makes sense because sediment discharge is a function of the streamflow available to transport sediment. Effects of streamflow are most striking when the average sediment yield from Blackwood Creek is compared with the average sediment yields from the other three study areas. During this study, average suspended-sediment yield from Blackwood Creek was 6.5 times greater than from General Creek, 14 times greater than from Edgewood Creek, and 97 times greater than from Logan House Creek. This large difference in sediment yields results, at least in part, from Blackwood Creek's higher average annual streamflow, which was 1.5 times that of General Creek, 4.2 times that of Edgewood Creek, and 8.8 times that of Logan House Creek (table 1).

In addition to the direct association between streamflow and sediment yield, lower amounts of runoff tend to produce narrower, shallower channels

Figure 10. Dense riparian vegetation along the stream channel of Edgewood Creek.

(Leopold and Maddock, 1953), as supported by data from Edgewood and Logan House Creeks. As mentioned previously, banks in these smaller channels have been buttressed effectively by riparian vegetation, further limiting erosion in these basins.

#### GEOLOGIC EFFECTS

Bedrock type and geologic history may affect sediment yields in the study basins. For example, glaciation in upper reaches of the General Creek basin effectively removed much of the soil and weathered rock, leaving behind large expanses of bare rock. Conversely, the unglaciated east side of Lake Tahoe has an abundance of deeply weathered granite, which produces large amounts of sand-sized material that can be easily transported. The high permeability of the resulting deep sandy soils on the east side of the lake somewhat counterbalances the sediment availability because runoff is attenuated with increasing permeability. Vertical hydraulic conductivity of the Toiyabe soils found on the east side of Lake Tahoe ranges from 152 to 508 mm/h (Candland, 1979), much higher than precipitation intensities or snowmelt rates that can be expected for the area. For example, Boone and others (1983) measured a maximum precipitation intensity of only 22 mm/h during the study of a small basin in the Carson Range near Glenbrook, Nevada.

### LAND-USE CONSIDERATIONS

Although several naturally occurring factors seem to control differences in sediment yields among the four study basins, both the Blackwood Creek and Edgewood Creek basins have a history of land use that has undoubtedly affected sediment yields from those basins. The suspended-sediment budget study was not designed specifically to address the effects of land use on sediment yields. However, results of this study could help to identify possible cause-and-effect relations between land use and sediment yields.

The sediment-budget study has identified stream channels as the dominant source of sediment in the four study basins (tables 12-15). It is especially important, therefore, to consider land-use effects on sediment yields because the form of alluvial channels found in the study basins represents a delicate balance between runoff and the volume and character of available sediment. Any change within a drainage basin that increases runoff or sediment supply could lead to changes in channel form that might further increase sediment discharge to Lake Tahoe.

#### INCREASED RUNOFF

The large area of impervious surface in the Edgewood Creek basin may have increased runoff and bed scour along upper reaches of Edgewood Creek (table 9). Streamflow from Edgewood Creek basin was about twice that of Logan House Creek basin during the study period (table 1) even though average annual precipitation in the two basins differs by only 8 percent--635 mm for the Edgewood Creek basin and 584 mm for the Logan House Creek basin (Hill and others, 1990). The vegetative buttressing along Edgewood Creek probably makes bed scour more efficient than bank erosion as a mechanism for increasing the channel cross-sectional area to accommodate increased streamflow. In addition, Hadley (1961) observed bed scour rather than bank erosion after tamarisk was established along the banks of a stream in Arizona. In the Blackwood Creek basin, logging roads established in the 1950's and 1960's, as well as the active road system, may have increased runoff. Because of the many factors involved, including variations in average annual precipitation and underlying rock type, the effects of land use in the Blackwood Creek and Edgewood Creek basins would have to be quantified by specific, process-oriented studies.

#### SEDIMENT SUPPLY

The suspended-sediment budget study indicates that bank erosion is high in the Blackwood Creek basin (fig. 9). Channels in the basin possibly are affected by past land use (such as logging, grazing, or gravel extraction) that increased sediment supply. Channels may have aggraded and widened to accommodate increased sediment. Unravelling this rather complex set of past conditions is difficult, and the task is further complicated by the occurrence of a major storm in 1964 (Nolan and Hill, 1987). This storm coincided with a period of logging and gravel extraction in the basin. Studies elsewhere in California (Knott, 1971; Harden and others, 1978; Lisle, 1981) have indicated that when such land-use activities and floods occur simultaneously, resulting large volumes of mobilized sediment can overwhelm the transport capacity of channels for decades.

Field observations indicate that roads in the Edgewood Creek basin are often covered by a thin veneer of sediment that either washes off adjacent cut slopes during periods of rain or snowmelt or moves off those slopes as dry ravel during dry periods. Some of this sediment probably enters the stream channel system. Two studies of highway effects on sediment supply in the Lake Tahoe basin have reached widely different conclusions. Kroll (1976) found that about 2 percent of all fine-grained-sediment discharge to the lake came from cut slopes along local highways. However, a study done in the upper Truckee River drainage basin by the California Department of Conservation (1969) estimated that 48 percent of the sediment entering the upper Truckee River (fig. 1) came from erosion associated with roads. The sediment observed on road surfaces in the Edgewood Creek basin seems to be a potential source of sediment that is absent in the Blackwood, General, and Logan House Creek basins. Lacking further data, however, the effects of road-related erosion on the suspended-sediment discharge from Edgewood Creek cannot be determined.

#### GULLY FORMATION

Data collected on gully volumes in the Blackwood and Edgewood Creek basins show direct land-use implications. All inventoried gullies were related directly to concentration of drainage, usually associated with road systems. The highly permeable soils found in the study basins do not seem naturally prone to gully development.

At least 2,800 $m^3$ of sediment in the Blackwood Creek basin and 320 $m^3$ of sediment in the Edgewood Creek basin were removed by gully erosion. The amount of time over which those volumes of sediment were removed is unknown; therefore, the data cannot be put into the time frame of the study. Some of the gullies could have been active for decades.

### RELEVANCE OF STUDY RESULTS TO LONG-TERM SEDIMENT LOADS

Both wet (1984 and 1986) and dry (1987) conditions occurred in the Lake Tahoe basin during the study (tables 1 and 2); therefore, the average annual suspended-sediment budgets developed by this study should characterize basin response to a wide range of future conditions. Sediment transport is episodic, however, and usually is affected strongly by periods of high flow. For example, 78 percent of the sediment transported in Blackwood Creek during 1984-87 was moved during the wet year of 1986, when sediment transport was dominated by major rain-on-snow events. The effect of a particular climatic event on sediment transport is highly variable and depends on the time of year and ground conditions when it occurs (Galton, 1984). Effects of future runoff events, therefore, are difficult to predict. An exceptionally intense storm in the future could remove large quantities of sediment from the study basins in a manner not in keeping with the sediment budgets developed for this study.

Data from Hill and others (1990) indicate that volumes of sediment many times greater than average annual sediment yields are readily accessible to active stream channels in the study area. Figure 11 shows the volume of sediment stored along main channels in the study basins. Virtually all grain sizes of this stored sediment could be mobilized by flows of moderate magnitude. Florsheim (1988) found that even cobbles and small boulders in bars along Blackwood Creek could be transported by flows having probable recurrence intervals greater than once in 20 years.

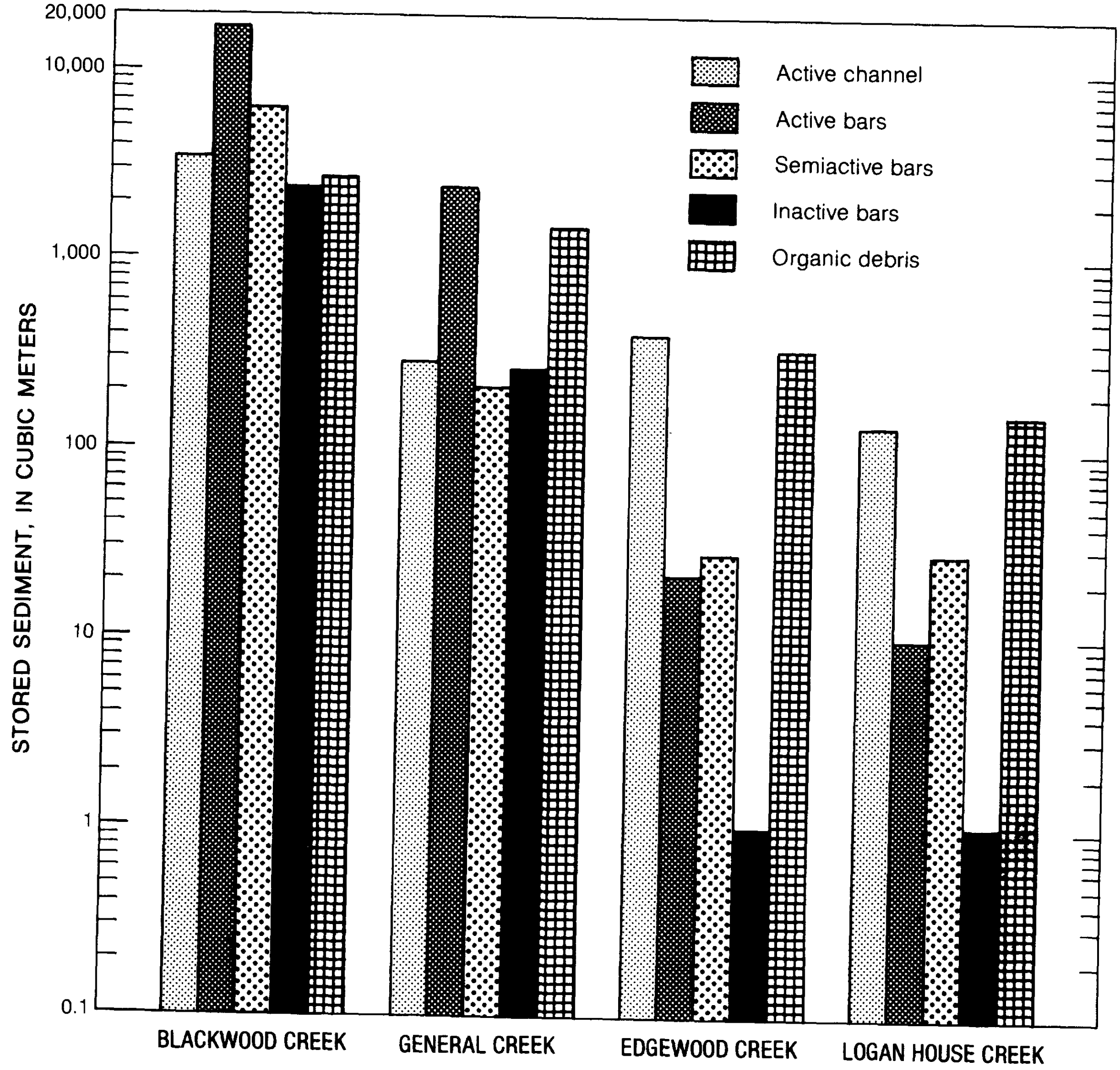

**Figure 11.** Volume of stored sediment, by category, along main channels in the study basin.

One possible drainage-basin response to a major runoff event, therefore, is that large volumes of this stored sediment could be mobilized and transported from storage. This response would represent channel behavior not considered in the suspended-sediment budgets developed for this study for Blackwood, Edgewood, and Logan House Creeks, which indicate that small percentages of mobilized sediment are derived from the streambeds of these three streams (tables 12-15).

## CONCLUSIONS

Sediment budgets for the Blackwood, General, and Edgewood Creek drainage basins have quantified the rates at which erosional processes were operating in these three Lake Tahoe tributary basins during 1984-87. Sediment-budget data for the Logan House Creek basin did not balance. Conclusions drawn from those data are, therefore, less certain than conclusions drawn from sediment budget data collected in the other three basins.

Although stream-channel processes were found to be more important than hillslope processes in the Blackwood, General, and Edgewood Creek basins, the rates of channel processes differ markedly from basin to basin. For example, average annual precipitation in the Blackwood Creek basin is higher than in any other study basin. As a result, runoff from the Blackwood Creek basin is higher than from any other study basin. The runoff, in turn, accelerates bank erosion. Stream channels in the Blackwood Creek basin are deeper than channels in the other basins. The banks of many channels in the Blackwood Creek basin are too high to be effectively buttressed by riparian vegetation, which is another reason why bank erosion rates in the Blackwood Creek basin are higher than in any other study basin. Sediment yields from Edgewood and Logan House Creeks are lower than yields from General or Blackwood Creeks. This is due, in large part, to the fact that average annual precipitation is lower and soils are highly permeable in the Edgewood and Logan House Creek basins. These two factors combine to produce less runoff from these basins than from the basins of General or Blackwood Creeks. Not only does this low runoff produce sediment yields that are lower than those from General or Blackwood Creeks, it forms relatively small stream channels with banks that are low enough to be effectively buttressed by riparian vegetation.

Geologic controls seem to limit the amount of sediment supplied directly from hillslopes to stream channels. By removing weathered regolith and forming wide, flat valley floors, glaciation has effectively decoupled the hillslopes from the main stream channels in the Blackwood Creek and General Creek basins. No major landslides were observed in the study basins during the study period.

Although the suspended-sediment budget study did not focus on the effects of land use on sediment yield, the study does help to identify possible cause-and-effect relations between land use and sediment yield. Field inspections and comparisons of suspended-sediment budget data for Edgewood and Logan House Creeks indicate that erosion of roadcut banks and gully erosion in Edgewood Creek probably have increased sediment supply and contributed to the large volumes of sediment stored along the streambed of Edgewood Creek. Erosion of this stored sediment, which could be facilitated by increases in runoff, might be a major reason why suspended-sediment yield from Edgewood Creek is so high in comparison to the suspended-sediment yield from Logan House Creek. Much of the evidence of land-use effects on sediment yield is drawn indirectly from results of the suspended-sediment budget studies. Any direct identification of cause and effect between land use and sediment yield would require additional studies.

Because the suspended-sediment budget study indicates that alluvial channels are the dominant source of sediment in the study basins, it is reasonable to expect that land-use changes virtually anywhere in a given basin could affect sediment yield. The form of alluvial channels in the study basins could change in response to changes in runoff or sediment supply, and these changes in channel form could result in increased sediment loads to Lake Tahoe. Effective land management, therefore, requires an understanding of how drainage-basin processes interact to affect channel form, and how proposed land-use changes might affect the interaction of such processes.

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