Streamflow, Sediment Transport, and Nutrient Transport at Incline Village, Lake Tahoe, Nevada, 1970–73

United States Geological Survey Water-Supply Paper 2313

Prepared in cooperation with the Nevada Division of Water Resources and Washoe County

Cover: Incline Village study area, Lake Tahoe, Nevada. Approximate drainage basin boundaries indicated by dashed, dotted lines. Solid triangles are principal data collection sites; solid squares are supplementary data collection sites.

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By PATRICK A. GLANCY

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Streamflow, Sediment Transport, and Nutrient Transport at Incline Village, Lake Tahoe, Nevada, 1970–73

By Patrick A. Glancy

Abstract

Five principal creeks, First Creek, Second Creek, Wood Creek, Third Creek, and Incline Creek, having a cumulative drainage of 17.8 square miles, furnished a yearly average of about 15,000 acre-feet of runoff, mainly snowmelt, to Lake Tahoe during the 1970–73 water years. Annual runoff from the individual streams ranged from 460 to 7,070 acre-feet, and discharges ranged from 0.2 to 110 cubic feet per second. During the 4 years, the five streams delivered to Lake Tahoe 31,000 tons of sediment, which averaged about 75 percent gravel and sand, 15 percent silt, and 10 percent clay. Annual cumulative sediment load for the five creeks ranged from 1,500 to 11,000 tons; individual streams furnished 20 to 5,200 tons annually. Measured sediment transport at the stream mouths ranged from 1 to 13,200 milligrams per liter and from 0.001 to 1,420 tons per day; sediment concentrations up to 63,200 milligrams per liter were measured at upstream tributary sites.

Estimated annual sediment yields of principal drainage basins ranged from 3 to 930 tons per square mile from undeveloped areas and from 26 to 5,000 tons per square mile from developed areas; yields for developed areas appeared to average about 10 times those of undeveloped areas, and roadways apparently were the major source. Erosion disequilibrium caused by prestudy flash floods on two of the creeks continues to manifest itself through high natural sediment yields. The Second Creek flood of 1967 yielded about 75,000 tons of sediment in one afternoon.

Fluvial nutrient transport seems quantitatively related to magnitudes of sediment and water transport. Movement rates of organic nitrogen and particulate phosphorus were greater than rates of other nutrient species moving to the lake.

INTRODUCTION

Environmental Problems and Information Needs

Possible environmental degradation of Lake Tahoe has been a subject of great concern for many years. The current eutrophication status of the lake and possible acceleration of eutrophication processes related to man's use of the basin have been of particular concern. Erosion, accelerated by urban development, and transport of eroded sediment and related biochemical nutrients to the lake have become key points of a controversy that centers around the role of human activity in accelerating the eutrophication process. However, quantitative data on natural drainage characteristics and on man's effects on the fluvial hydrologic processes of Lake Tahoe tributaries are scarce. Also, interrelations of stream-borne nutrients and water-sediment mixtures generally are poorly understood (Lee, 1970). Consequently, speculation continues to be a significant characteristic of the controversy regarding Lake Tahoe and its environment.

Objectives of this Study

As a result of the hydrologic-data needs in the northeastern part of the Lake Tahoe basin, the U.S. Geological Survey, in cooperation with the Nevada Department of Conservation and Natural Resources, initiated a reconnaissance investigation of streamflow and sediment transport in the Incline Village area (fig. 1). Incline Village is the developed part of this northeastern area of the Tahoe basin. This planned 5-year study began in October 1969 (start of the 1970 water year) but terminated after 4 years because of a shortage of funding.

Major objectives of this study were to (1) numerically assess runoff from the major stream drainages and characterize runoff timing with respect to seasons and climate, (2) numerically assess fluvial-sediment transport as accurately as possible by using reconnaissance techniques, and (3) provide preliminary data on the nutrients (mainly nitrogen and phosphorus compounds) transported to the lake by the water-sediment mixtures of streams.

This summary report, which was preceded by three progress reports that documented streamflow and sediment transport on an annual basis (Glancy, 1971, 1973,

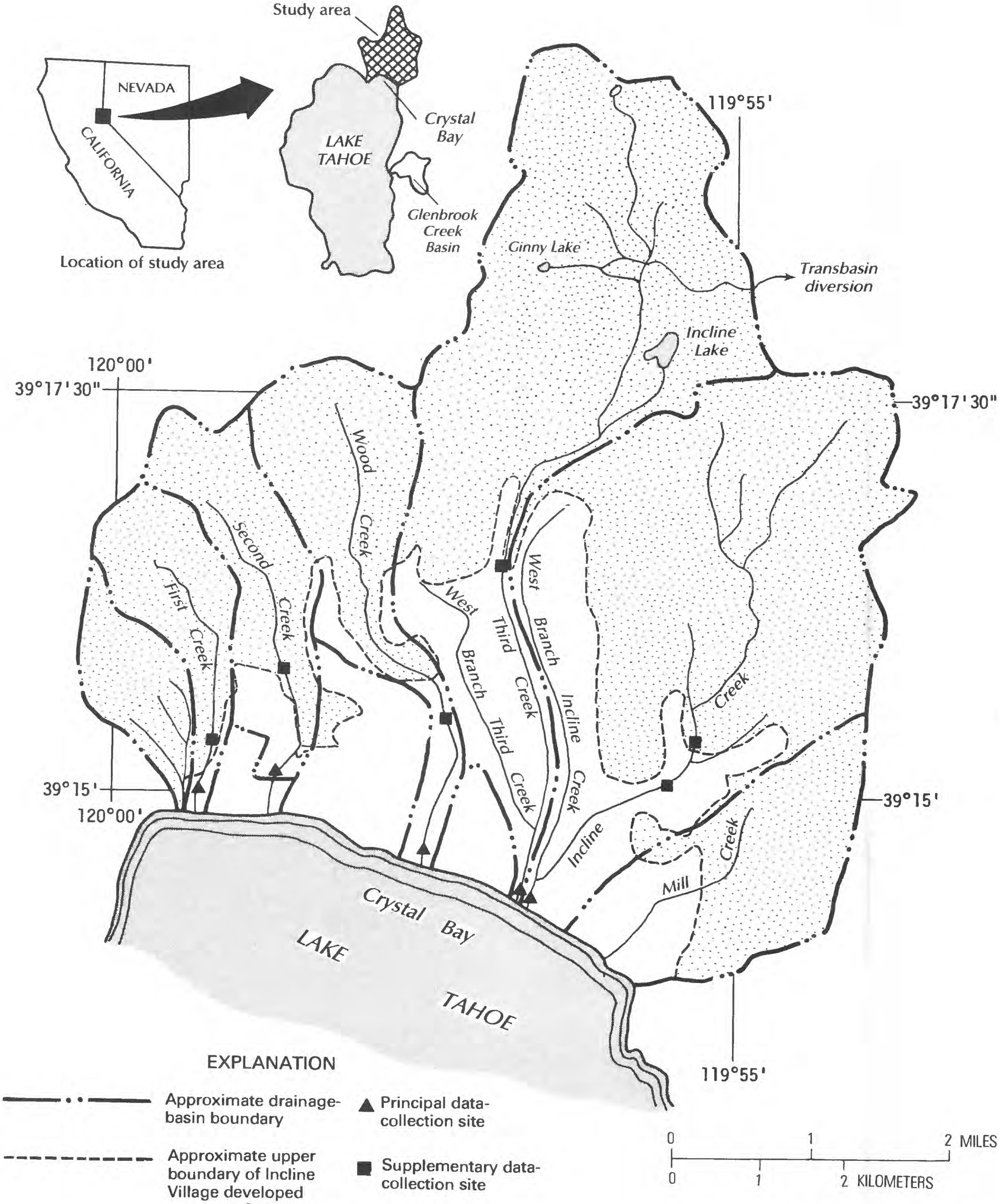


Figure 1. Incline Village area. Stipple pattern indicates undeveloped area.

and 1976a), was prepared in cooperation with the Nevada Division of Water Resources and Washoe County.

Data Collection and Analysis

Essential data involved concurrent measurements of streamflow and collection of water samples to define concentrations of sediment and particle-size distribution in the flow. These two parameters were used conjunctively to compute sediment discharges (loads) for the respective measurement sites. Streamflows of Incline and Third Creeks were monitored near their mouths by continuous recorders (fig. 1). Streamflow data for these creeks are presented in four volumes of "Water Resources Data for Nevada" (U.S. Geological Survey, 1971, 1972, 1973, and 1974). Streamflows of Wood, Second, and First Creeks, near their mouths, were synthesized by using instantaneous-flow measurements. These flow data were correlated with the continuously recorded streamflows of Incline and Third Creeks.

Sediment data were collected to span as broad a range of transport conditions as possible. A relatively small number of samples that defined general sediment-transport characteristics during periods of low streamflow were collected. The most frequent and intensive sampling was done during periods of high streamflow when fluvial-sediment transport was greatest. Samples were analyzed for sediment concentration and particle-size distribution by using standard U.S. Geological Survey techniques (Guy, 1969).

Total-sediment transport parameters were measured in this investigation because the data were collected at streamflow waterfall sites that allowed both lateral- and depth-integrated sampling through the entire flow. The open mouths of sediment bottles were used generally as the sampling nozzle orifices to capture larger sediment particles than would be possible with standard sediment-sampling nozzles. In spite of technical deficiencies inherent in this technique, the data are probably more accurate regarding total sediment transport than those that might otherwise have been calculated by using the more traditional suspended-sediment measurement data.

Most fluvial-sediment investigations involve measurement of only suspended-sediment parameters rather than total-sediment parameters and thus provide direct-measurement data of some generally indeterminate fraction of the total-sediment movement. This undesirable feature is inherent in most studies because the physical and hydraulic characteristics of most measurement sites do not permit the direct measurement of total-sediment transport parameters. When only suspended-sediment parameters are measured, total-sediment transport must then be computed by combining the suspended fraction with a computed or estimated bedload fraction of the total-sediment load.

Daily sediment discharges of Incline and Third Creeks near their mouths were computed from the total-sediment measurements according to standard U.S. Geological Survey methods (Porterfield, 1972). During periods when no sediment data were collected, daily sediment discharges were estimated by interpolating between days on which data were collected; careful attention was given to changing streamflows and weather conditions to improve interpolation accuracy. Sediment discharges of Wood, Second, and First Creeks near their mouths were estimated by using families of sediment-transport rating curves that were developed from available sample data and from daily water discharges of the synthesized hydrographs. Estimates were tempered on the basis of personal observations of erosion and streamflow conditions. This method of estimating sediment discharges was patterned in part after techniques described by Colby (1956).

The specific conductance of each sample of water-sediment mixture was determined to provide insight and perspective on general streamflow salinity and salinity fluctuations of various sources of streamflow in the study area.

Nutrient-sampling methods required immediate chilling of samples to temperatures below 4 °C and filtering of appropriate parts of the samples as soon as possible. Samples were retained at cold temperatures and analyzed as quickly as possible. Nutrient analyses for the first study year were made at the U.S. Geological Survey California District Laboratory in Sacramento, Calif. Analyses for the final 3 study years (1971–73) were made at the U.S. Geological Survey Central Laboratory in Salt Lake City, Utah. Interpretations in this report rely mainly on nutrient data collected during the final 3 study years because sampling site locations were modified after the first year.

The principal hydrologic data-collection sites and some of the more important supplementary data-collection sites are shown in figure 1. All supplementary data sites are shown in a publication of miscellaneous hydrologic data collected during the course of this investigation (Glancy, 1976b, pl. 1). All the data collected at the principal data sites, as well as the data collected at the Wood and Third Creeks supplementary sites (see fig. 1), were published in progress reports of this investigation (Glancy, 1971, 1973, and 1976a).

The data summaries and interpretations of this report are based on about 2,750 sediment-concentration analyses, 200 sediment particle-size distribution analyses, and 50 nutrient analyses. The bulk of the data was collected from five perennial streams near their confluence with Lake Tahoe, in keeping with the major study objective of determining transport rates of water-sediment mixtures to Lake Tahoe. Specifically, about 1,800 sediment-concentration samples and roughly 160 sediment particle-size distribution samples were collected from the five principal creeks near their mouths. Also, about 40 nutrient samples were collected near the mouths of Incline and Third Creeks, which are the major drainages of the study area in terms of total water discharge to Lake Tahoe. The remainder of the data was collected at supplementary sites to try to determine principal areas of fluvial-sediment origin, to improve understanding of sediment movement within developed areas, and to help determine differences in sediment yields from developed and undeveloped areas.

Qualifications Regarding the Use of this Report

This report is a general assessment of hydrologic conditions in the Incline Village area during a specific time period. The knowledge gained by the investigation provides perspective on both natural and urban-development hydrology at Lake Tahoe and, to a lesser degree, contributes perspective on the hydrologic problems of urban development in the Sierra Nevada and other mountainous areas.

The numerical data and their interpretations apply only to the study period unless otherwise specified. Because of the dynamic character of urban development in the study area during recent years, users of this report are cautioned that the data and conclusions of this investigation are chiefly representative of only the brief study period and thus preclude a statistically significant sampling of natural hydrologic variability. The data and their interpretations are not meant to be extrapolated to other parts of the Tahoe basin or other Sierra Nevada areas because hydrogeologic conditions probably vary greatly from place to place and from time to time. Finally, the data collection network and study objectives were not designed to describe precisely the processes of erosion and sediment yield from small land plots or to pinpoint all significant sources of intense sediment discharge.

STUDY AREA CHARACTERISTICS

Physiography

The Incline Village study area is an irregular 21.9-mi^2 composite of mostly small drainage basins tributary to Crystal Bay in the northeast (Nevada) part of Lake Tahoe (fig. 1). Each of the five principal drainages that collectively make up most of the study area (First, Second, Wood, Third, and Incline Creeks) is elongate, with its major axis generally north-south aligned. The area lies completely within the Sierra Nevada mass and is dominated by south-facing slopes. Approximate maximum altitudes in the five principal tributary drainages of the area are First Creek, 9,270 ft; Second Creek, 9,610 ft; Wood Creek, 9,710 ft; Third Creek, 10,340 ft; and Incline Creek, 9,225 ft. The legally decreed maximum altitude of Lake Tahoe (maximum base level of Incline Village area streams) is 6,229.1 ft. Lake levels are largely controlled by regulated releases of streamflow to the Truckee River. The maximum relief of the Third Creek drainage basin, approximately 4,100 ft, is greater than the relief of any other area tributary to Lake Tahoe.

Table 1 lists areas of the principal drainages and of their undeveloped and developed segments. Longitudinal profiles, average gradients, and altitude-area relations of the five principal drainages are shown in figure 2. The profiles were derived from the U.S. Geological Survey Mount Rose and Marlette Lake, Nev., 7½-minute quadrangle topographic maps. Although First, Second, and Wood Creeks' drainage areas are similar in size, each has a unique distribution of area-altitude zones. The most striking differences in area-altitude distributions are those of Third and Incline Creeks; although both creeks have similar drainage-area sizes, their area-altitude distributions are very different. The area-altitude distribution differences explain, at least in part, notable differences in runoff characteristics of the two creeks (see Runoff Characteristics of Principal Drainage Basins section).

First, Second, and Wood Creeks each consists principally of only one perennially flowing stream, except in its uppermost reach where minor branching occurs. In contrast, the larger drainages of Third and Incline Creeks contain several different orders of perennial tributaries. The initial branching of both Incline and Third Creeks occurs within one-half mile of their mouths.

Figure 2 shows that drainage-area sizes and complexities of main stream-channel profiles generally tend to increase from west to east. First Creek's profile consists principally of two major gradient segments, whereas Second and Wood Creeks' profiles consist each of about four segments. The main-channel profiles of Third and Incline Creeks consist of probably no less than 10 major gradient segments each.

Main-channel lengths, as scaled from the longitudinal profiles (fig. 2), also generally fit the west-to-east pattern of increasing magnitude. Approximate lengths are First Creek, 4.00 mi; Second Creek, 4.45 mi; Wood Creek, 5.35 mi; Third Creek, 8.30 mi; and Incline Creek, 5.77 mi.

Vegetation

The study area generally is quite heavily forested. However, the Mount Rose quadrangle map and aerial photographs show substantial unforested terrain in the headwaters of First, Second, Wood, and Third Creeks. Figure 3 shows that vegetative cover is nonuniform and generally patchy throughout much of the area. The dense

Table 1. Drainage areas of individual basins

Drainage areas for natural (predevelopment) conditions

Drainage unit	Total area[1] (square miles)	Percentage of entire study area	Approximate area outside general urban development boundary[1] (square miles)	Approximate area within general urban development boundary[1] (square miles)	Area within development boundary as a percentage of total area
Tributary west of First Creek	0.67	3	0.67	0.004	0.6
First Creek	1.09	5	1.01	.08	7
Second Creek	1.81	8	1.18	.63	35
Ephemeral tributaries between Second and Wood Creeks	1.00	5	.14	.86	86
Wood Creek	2.03	9	1.46	.57	28
Ephemeral tributaries between Wood and Third Creeks	.28	1	.00	.28	100
Third Creek	6.03	28	4.74	1.29	21
Incline Creek	6.98	32	4.90	2.08	30
Mill Creek	2.02	9	1.29	.73	36
Entire study area (rounded)	21.9	100	15.4	6.5	30

Drainage areas of principal streams, as modified by man's development[2]

Stream	1970 water year			1971–73 water years		
	Developed	Undeveloped	Total[3]	Developed	Undeveloped	Total[3]
First Creek	0.10	1.04	1.14	0.16	1.01	1.17
Second Creek	.17	1.41	1.58	.38	1.18	1.56
Wood Creek	.57	1.46	2.03	.57	1.46	2.03
Third Creek	1.19	4.84	6.03	1.29	4.74	6.03
Incline Creek	1.85	5.13	6.98	2.08	4.90	6.98
Total (rounded)	3.9	13.9	17.8	4.5	13.3	17.8

[1] Areas listed are those bounded by natural topographic divides.
[2] In square miles.
[3] Areas are those tributary to principal data-collection sites near stream mouths. They include obvious modifications of natural drainage boundaries by man's development. Several estimates differ from those published earlier in progress reports (Glancy, 1971, 1973, and 1976a). Reasons for differences are discussed in Sediment Yields section of this report.

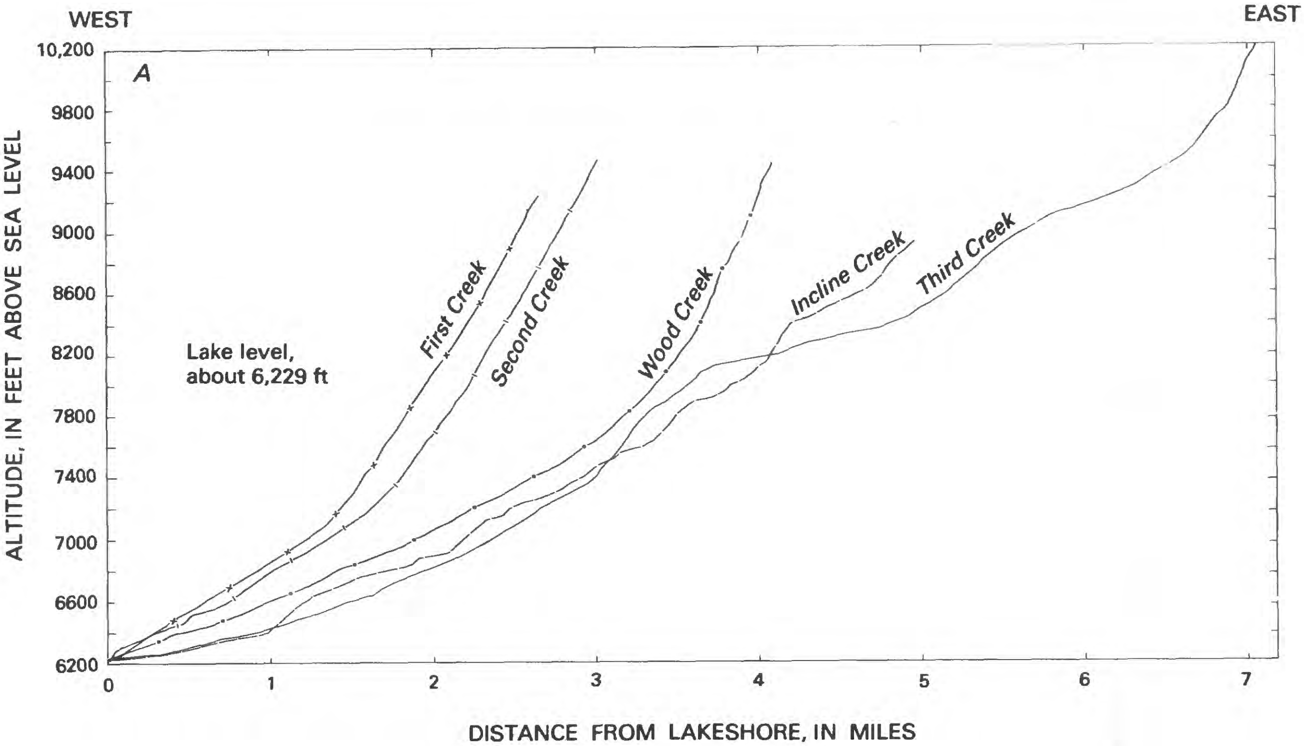
natural vegetative cover that existed in lowland areas prior to recent development (fig. 3*A*) has been considerably modified and thinned (fig. 3*B* and *C*).

Heavy logging operations during the late 19th century are believed to have virtually denuded the study area of its forest cover (see section on Development History). Thus, today's vegetation is mainly second growth, replacing that removed by man's earlier modifications of the natural environment.

The scope of this investigation did not allow an analysis of the influence of vegetation on the area's hydrology. Some interpretation of the relations between vegetative cover and characteristics of runoff and erosion is included in an earlier report on flooding in the Second Creek drainage (Glancy, 1969).

Geology and Soils

The geology of the study area has been mapped (Thompson and White, 1964, pl. 1; Mathews, 1968, p. 125). The available maps emphasize bedrock geology; they do not delineate surficial geology in the detail needed to clearly define hydrologic characteristics in terms of geologic influences. Most of the highland bedrock areas consist of either granodiorite of the Sierra Nevada batholith of Cretaceous age or volcanic rocks of Tertiary age. Lowland areas are generally mantled by deposits of stream-laid alluvium and lake sediments of Quaternary age. Higher valley areas, mainly in the Third Creek drainage, also contain unconsolidated glacial deposits. Thus, streamflow contacts a large variety of lithologic constituents that range widely in erosion potential. Major stream channels are lined throughout most of their courses by varying thicknesses of unconsolidated alluvium. This alluvium generally has a high potential for movement, and its erosional stability is therefore quite sensitive to changes in stream regimen. Geologic characteristics that relate to specific streamflow and sediment-transport conditions are discussed in the Sediment Transport section of this report.



B

	Average main-channel gradient (feet per mile)	Area[1] (square miles)	Approximate percentage of drainage area within different altitude zones				
			Below 7,000 feet	7,000–8,000 feet	8,000–9,000 feet	9,000–10,000 feet	Above 10,000 feet
Tributary west of First Creek	([2])	0.67	26	63	11	0	0
First Creek	1,130	1.09	17	35	40	8	0
Second Creek	1,080	1.81	32	30	23	15	0
Ephemeral tributaries between Second and Wood Creeks	([2])	1.00	84	16	0	0	0
Wood Creek	790	2.03	19	33	34	14	0
Ephemeral tributaries between Wood and Third Creeks	([2])	.28	100	0	0	0	0
Third Creek	560	6.03	17	13	35	34	1
Incline Creek	540	6.98	21	43	35	1	0
Mill Creek	([2])	2.02	42	42	16	0	0
Total	--	21.9	--	--	--	--	--

[1]Areas listed are those bounded by natural topographic divides. Drainage areas as modified by man's development are shown in table 1.
[2]Not determined; profile not plotted.

Figure 2. *A*, Longitudinal profiles of the principal streams and, *B*, area-altitude distribution of principal drainages.

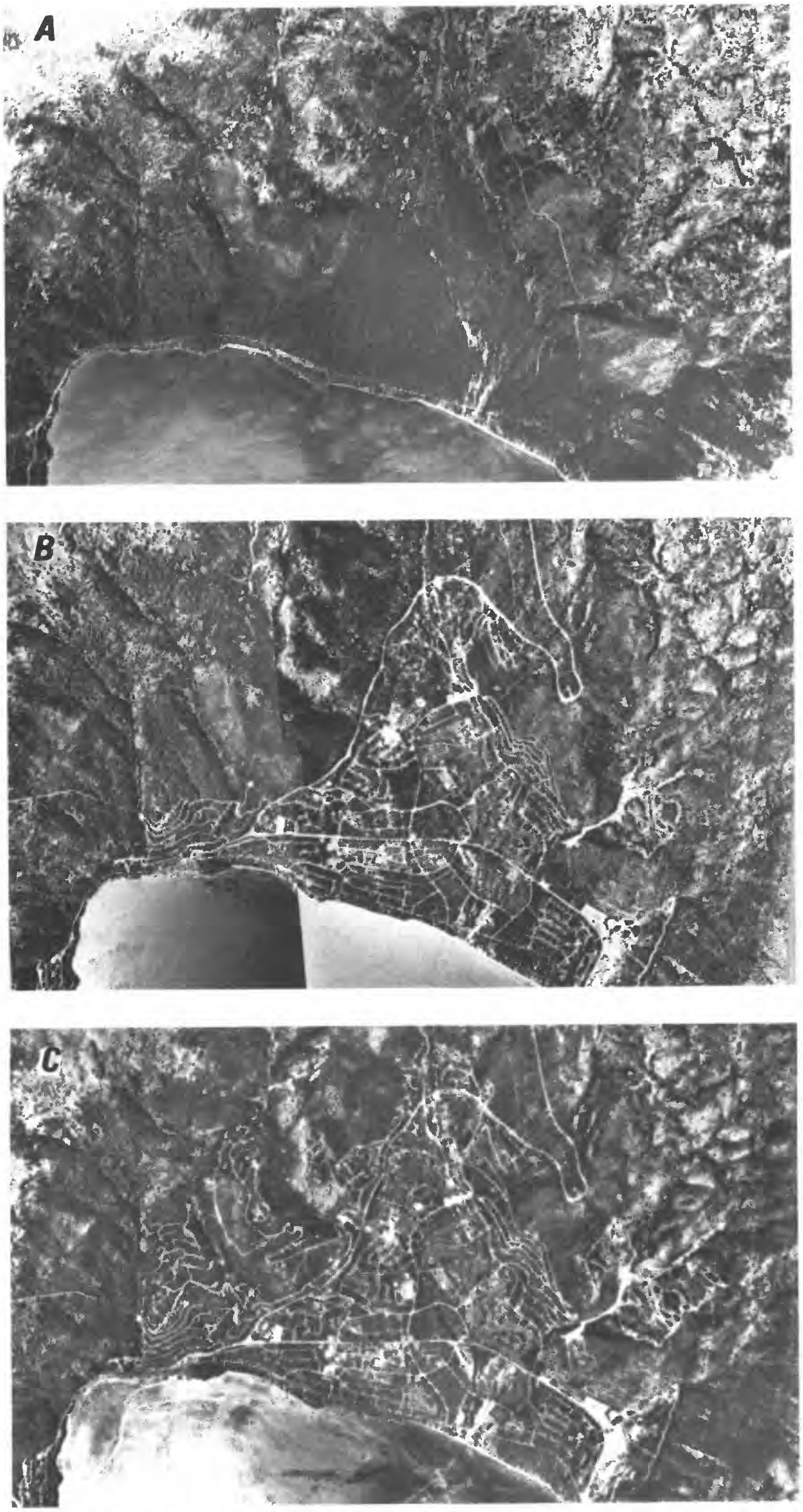


Figure 3. Sequence of vertical aerial photographs, showing evolution of development in the study area. *A*, November 20, 1956 (U.S. Army Map Service); *B*, June 18, 1966 (U.S. Geological Survey); and *C*, August 19, 1973 (U.S. Forest Service).

Soils of the area and their hydrologic characteristics are described in detail by Kennedy and Rogers (1971).

Precipitation

There are no known published long-term precipitation data for the study area. Several estimates of ranges in annual precipitation have been published as part of at least three isohyetal maps. The approximate ranges in average annual precipitation in the area, as shown by the published isohyetal maps, are 23 to 30 in. (McGauhey and others, 1963, figs. 3–6), 30 to 47 in. (Crippen and Pavelka, 1970, p. 21), and 24 to 46 in. (James, 1971, map following p. 6).

Dr. John James, a meteorologist of Mountain West Weather Service, analyzed 8 years of precipitation data from Incline Village and longer term records of other Tahoe basin precipitation measurement stations. He concluded that annual precipitation in the Incline Village area at about the 6,500-ft level averages 24.8 in. He also estimated that, on the average, 65 to 70 percent of the precipitation at the 6,500-ft level is snowfall (John James, oral commun., 1976).

At altitudes below 7,000 ft, the annual percentage of precipitation that is snowfall varies greatly, and mixed conditions of rainfall and snowfall occur frequently during autumn, winter, and spring. Recurring conditions of alternating snow-covered and bare ground are common and, at lower altitudes, have pronounced short-term effects on streamflow and sediment-transport conditions, particularly when the natural runoff regime is modified by development. Snowpack accumulation and runoff conditions are more stable and constant at higher and generally colder altitudes, which are also the areas of greater precipitation.

The specific manners in which snowpacks accumulate and dissipate strongly affect the runoff character and streamflow at any given time. These resultant runoff characteristics, in turn, strongly influence sediment transport (see Runoff section).

Development History

The intensive logging operations of 1875–97 were modern man's first large-scale activities in the study area. A brief account of these operations is given by E.B. Scott (1957, p. 317, 318). The intensity of logging in the Crystal Bay area of Lake Tahoe, general locality of the present study, is demonstrated in this quotation of Scott, "By the summer of 1895 the mountainsides surrounding the bay were stripped clean...." (1957, p. 318). He concludes, "Today, to the north of Crystal Bay, 50 square miles of second growth pine carpets the slopes. Unfortunately, the pine and cedar giants that once covered the region are gone, only their rotting five and six foot high winter cut stumps remaining as skeletal reminders of the unrestricted logging methods employed by the early lumber companies."

Virtually nothing is known about past and residual effects of these logging operations on the lake. However, intensive logging operations elsewhere have been investigated in recent years, and results of several studies indicate that logging can have dramatic effects on streamflow and sediment transport. Therefore, we may assume that the old logging operations at Lake Tahoe altered the runoff and increased sediment transport to the lake, probably to a marked extent.

Livestock grazing, mainly by sheep, throughout the nonforested headwater segments of the area also affected vegetative growth and regrowth during postlogging years. However, again, no quantitative assessment of these effects is known to the author.

During the half century following logging, vegetation regrowth apparently was well reestablished. Figure 3*A*, an aerial photograph taken in November 1956, shows the general study area as a near-pristine, natural-appearing landscape north of Crystal Bay. The only visible signs of man's encroachment are a few roads and one small, obscure subdivided tract at the lower right part of the photograph between the sharp bend of the lakeshore highway and the lake. Vegetation density appears greatest in the low and midland areas surrounding the lower reaches of Wood, Third, and Incline Creeks.

Figure 3*B*, the same general area photographed about 10 years later, in June 1966, presents a sharp contrast to the earlier photograph. Subdivision activity was well underway, and major highways had been almost completely realigned. Vegetation patterns in the developed areas had been noticeably thinned to make way for subdivision roadways, a golf course, commercial and industrial sites, a ski run, service facilities, and numerous but less visible homesites.

The same general area, as viewed about 7 years later in an August 1973 aerial photograph, is shown in figure 3*C*. This photograph, taken during the 1970–73 water-year study period, documents the development activities that postdated those shown in the 1966 photograph. The most noticeable additions after June 1966 are the subdivision upgradient from the Mount Rose Highway, development of Incline Village Unit 3 and its additional golf course just south of the large open bend of the Mount Rose Highway, apparent expansion of the ski area at the right center of the photograph, and the Tyrolian Village subdivision north of the ski area.

The three aerial photographs provide a time-lapse visual sequence of modern day land-use changes in the study area. The photographs document the large degree of development that occurred prior to the beginning of this study in October 1969 and show that development also took place during the course of the investigation. Thus, the study was conducted during a dynamic nonequilibrium period in the history of drainages tributary to Crystal Bay. Figure 4 and table 2 provide more specific documentation of the history of development activity.

RUNOFF

General Characteristics of Runoff

Runoff occurs in one or a combination of three basic modes: (1) base flow fed by ground water, (2) rainfall runoff, and (3) snowmelt runoff. All three runoff modes can function concurrently in the principal streams of the area. Snowmelt and (or) rainfall runoff, added to the base flow, are responsible for most fluvial-sediment transport; only minor amounts of sediment normally are transported by base flow. Base flow is the dominant component of flow later referred to in this report as seasonal low flow.

Storm runoff generally recurs frequently during the autumn when rainstorms are common in the Tahoe basin. During late autumn and spring, brief periods of low-altitude mixed rain and snowmelt runoff commonly accompany or follow numerous rainstorms and snow flurries. Pulses of low-altitude snowmelt runoff occur frequently during autumn, winter, and spring as the snowpack below 7,000 ft fluctuates with alternating periods of snowfall and melting. The lowest altitude areas, particularly those below 6,500 ft, do not readily accumulate and store snowpack for prolonged periods, except during the colder parts of the winter. As a result, the ground surface of areas generally below 7,000 ft, and particularly those below 6,500 ft, is recurrently flushed by runoff, and this flushing greatly increases sediment mobilization in these areas.

Runoff Characteristics of Principal Drainage Basins

Snowmelt runoff is normally the major component of annual runoff to Lake Tahoe from any of the principal study-area drainages. Snowmelt runoff usually occurs over a several-month period and is frequently interrupted by storms and their accompanying cold temperatures. These interruptions result in numerous start-stop-start runoff sequences throughout the snowmelt season. Also, snowmelt-runoff magnitude pulses on a daily basis because of daily temperature fluctuations. Thus, dissipation of the winter snowpack involves a complex composite of numerous runoff pulses and interruptions.

The importance of snowpack melt is emphasized in figure 5, which shows that the bulk of study-period runoff of all five principal drainages occurred during spring and early summer. The general curve shapes for First, Second, Wood, and Incline Creeks are similar during the snowmelt runoff period. However, First, Second, and Wood Creeks exhibited sharper snowmelt runoff rises and recessions, and their snowmelt-runoff peaks were more intense than those of Incline Creek. The different character of Third Creek snowmelt runoff is shown by its uniquely shaped curve.

Streamflows to the lake from the five principal study drainages during the investigation, including runoff quantities and annual runoff yields (annual runoff divided

Table 2. Partial chronological listing of select development tracts

[This table and figure 4 differentiate major subdivision and development tracts and a select few minor tracts. Subdivisions and developed areas that involved substantial street construction or other landscape changes that may affect hydrology of the area were selected for inclusion]

Subdivision or tract number as shown in figure 4	Subdivision or tract name	Approximate time of development[1]
1	Unnamed	Pre-1956
2	Mill Creek Estates	1960
3	Lakeshore	1960–62
4	Ponderosa	1960–62
5	Chateau Acres	1960–63
6	Lakeview	1961–62
7	Winding Wood	1961–62
8	Wood Creek	1962
9	Edgewood Park	1962
10	Fairway Estates	1962–67
11	Golf Course	1963–64
12	Northwood	1963–67
13	Industrial #1	1963–70
14	Industrial #2	1964–65
15	Crystal Shores	1964–65
16	Ski Incline	1965
17	Woodridge	1965
18	Southwood	1965–67
19	Country Club Homes	1965–69
20	Country Club of Incline	1965–70
21	Fairway Park	1966
22	Commercial #1	1967
23	Tyrolian Village	1967–69
24	Lakeshore Terrace and Crystal Bay Cove	1968
25	Incline Village, unit 1	1968–69
26	Incline Village, unit 1A	1968–69
27	Whispering Pines	1968–69
28	Mountain Shadows	1968–72
29	Incline Village, unit 1B	1969
30	Incline Village, unit 2	[2]1969
31	Incline Village, unit 3	1969
32	Scotchwood	1969–70
33	Kings Castle	1969–70
34	Incline Village, unit 4	1970
35	Incline Village, unit 5	1970

[1] Approximate development dates were determined from files of Washoe County Engineer and oral communication with Harold Tiller, long-time resident of Incline Village, in 1976.

[2] Underwent street and tract development during study period.

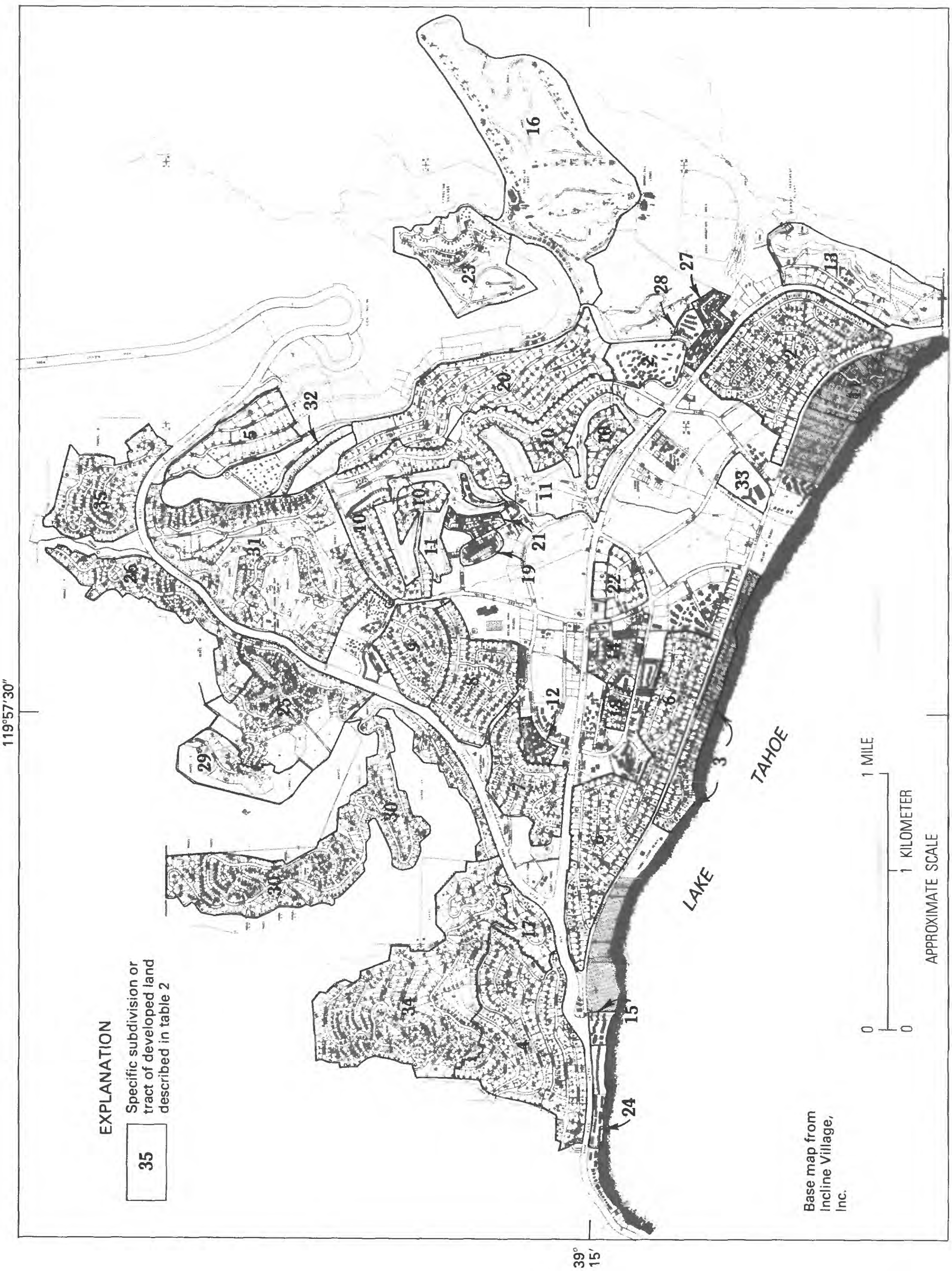


Figure 4. Major subdivisions and development tracts in the Incline Village area.

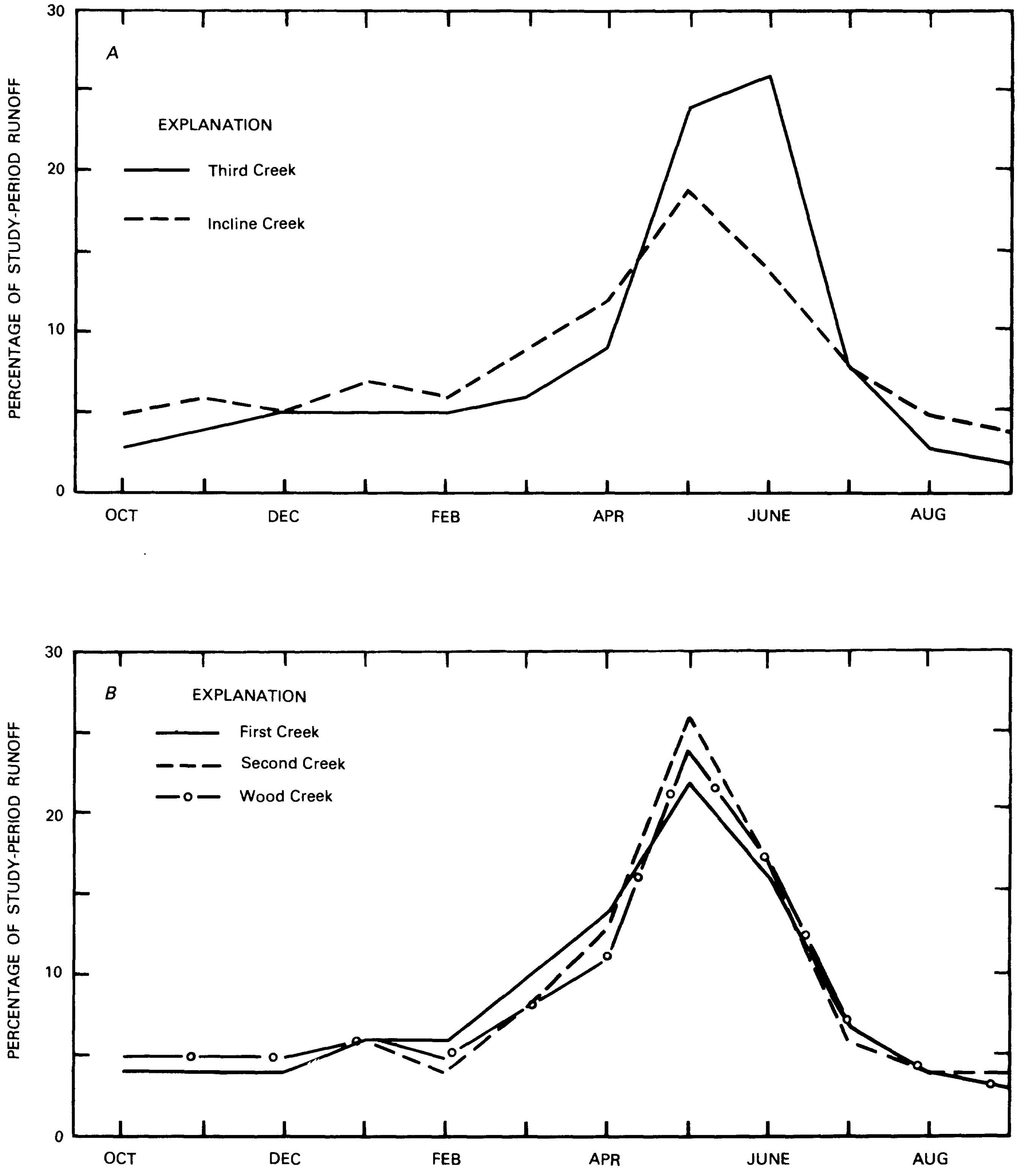


Figure 5. Monthly runoff of principal streams near their mouths as a percentage of study-period runoff. *A*, Third and Incline Creeks. *B*, First, Second, and Wood Creeks.

by drainage area), are summarized in table 3. Annual maximum and minimum flow rates of these principal creeks are summarized in table 4. Monthly and daily flow rates of Third and Incline Creeks were published in U.S. Geological Survey annual data publications (U.S. Geological Survey, 1971, p. 110–111; 1972, p. 109–110; 1973, p. 121–122; 1974, p. 126–127), and monthly runoff summaries of First, Second, and Wood Creeks were published in study progress reports (Glancy, 1971, p. 8; 1973, p. 10; 1976a, p. 10–11).

Table 5 tabulates estimates of mean annual runoff of the principal creeks for this study. For comparison, the table also includes the estimates from different studies that were derived by using different techniques. Qualitative descriptions of runoff events as they related to weather conditions on a year-to-year basis were summarized in previously published progress reports (Glancy, 1971, p. 7; 1973, p. 9–11; 1976a, p. 9, 12).

Relations of runoff to drainage-area size and sediment load are shown or can be deduced from data from tables 1, 3, 5, 10, and 11. Runoff generally increases with the increasing size of drainage areas. However, the annual runoff of Third Creek exceeds that of Incline Creek, contrary to the normal relation between runoff and drainage-area size, as shown in figure 6, mainly because of differences in the area-altitude distributions of the two drainages (fig. 2). The generally higher topographic distribution of the Third Creek basin causes increased precipitation and a correspondingly greater runoff.

The area-altitude distributions of Incline and Third Creek drainages are also major influences in determining the shapes of flow duration curves for these two streams (fig. 7). The curve for Third Creek depicts that stream as flashier (rises and recedes more rapidly in response to precipitation and snowmelt) in its runoff character than Incline Creek. The curves show that flow rates of Third Creek exceeded those of Incline Creek during 12 percent of the time during the period of study when streamflow rates of these creeks were greatest. Third Creek also has greater maximum annual peak discharges during most years (table 4). The generally more intensive high-flow rates of Third Creek are a major factor in the sediment-yield differences of the two drainages.

The flashy runoff nature of Third Creek may be enhanced partly by the delayed melting of high-altitude snow. On occasion, persistent cooler temperatures at high altitudes restrain spring snowmelt until the arrival of a hot spell in late spring or early summer; this postponed and reinvigorated snowmelt then causes intensive high-altitude runoff. For example, the peak flow rate of the study period (110 ft^3/s) occurred in Third Creek on June 26, 1971, following an approximately 10-day period during which maximum temperatures in Reno were mainly in the 80 to 90 °F range. That 10-day time was the first markedly hot weather period of the year. In contrast, Incline Creek snowmelt runoff had peaked a full month earlier, following a prolonged period of mildly warm weather during which Reno maximum temperatures were mainly in the 60 to 70 °F range. Peak spring-snowmelt discharge rates of Third Creek appear to always lag behind those of Incline Creek, sometimes by as much as a month. Peak snowmelt discharges are sometimes augmented or originated by rainfall on snowpack, as was the case in Incline Creek during 1970 and 1973.

The flow-duration curves of figure 7 show Third Creek discharge rates to be less than those of Incline Creek during medium- and low-flow periods. This difference is caused mostly by diversion of flow out of the Tahoe basin from the headwater area of Third Creek (fig. 1). Data collected during the 1972 and 1973 water years suggest that these transbasin diversions may average between 500 and 1,000 acre-feet annually (Glancy, 1976a,

Table 3. Annual runoff of principal streams into Lake Tahoe

[Upper number, runoff, in acre-feet; lower number (in parentheses), yield, in acre-feet per square mile. Drainage areas of table 1 used to compute yields]

Stream	Water year 1970	1971	1972	1973	4-year total (rounded)	Percentage of five-stream total
First Creek	900 (790)	910 (780)	460 (390)	700 (600)	3,000	5
Second Creek	1,300 (820)	1,500 (960)	790 (510)	1,100 (710)	4,700	8
Wood Creek	2,000 (990)	1,700 (840)	750 (370)	1,200 (590)	5,600	9
Third Creek	6,570 (1,100)	7,070 (1,170)	3,830 (640)	6,100 (1,010)	23,600	40
Incline Creek	6,940 (980)	6,450 (920)	3,810 (550)	5,100 (730)	22,200	38
Total (rounded)	17,600	17,600	9,600	14,200	59,000	100

Table 4. Summary of instantaneous water-discharge extremes for principal streams near their mouths

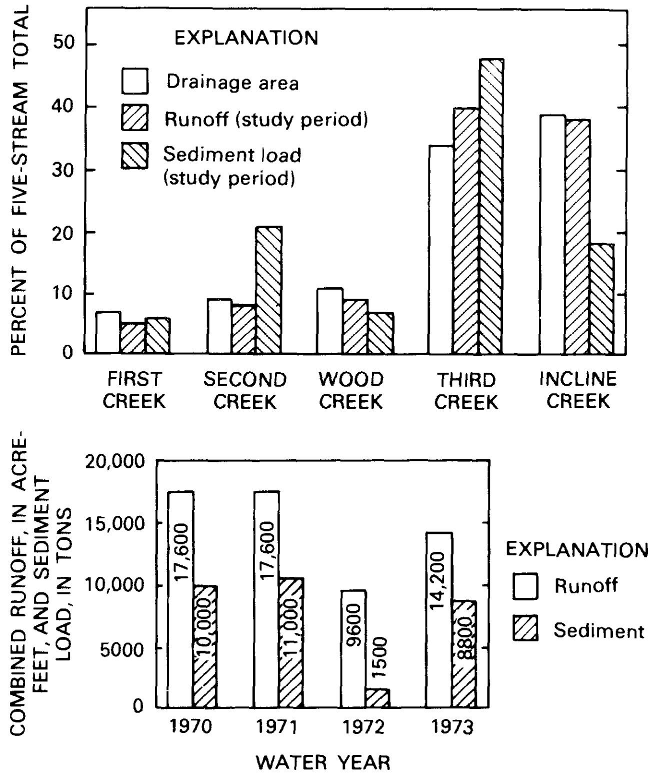
[Water discharge in cubic feet per second]

Stream	1970 Min.	1970 Max.	1971 Min.	1971 Max.	1972 Min.	1972 Max.	1973 Min.	1973 Max.
First Creek	0.2	11	0.2	10	0.4	2	0.3	6
Second Creek	.4	16	.5	15	.4	7	.4	11
Wood Creek	.8	15	.6	11	.2	4	.3	11
Third Creek	.8	65	1.1	110	.6	34	1.0	80
Incline Creek	1.7	87	2.1	38	1.5	18	1.7	40

Table 5. Estimates of mean annual runoff of principal streams to Lake Tahoe
[Runoff in acre-feet per year]

Stream	Determined from data of this study	McGaughey and others (1963, p. 15)	Channel geometry technique (Moore, 1968, p. 36–38)	Regional runoff-altitude technique[1]
First Creek	800	900	1,000	1,200
Second Creek	1,200	1,230	700	1,800
Wood Creek	1,300	1,470	1,200	2,200
Third Creek	6,400	3,800	6,500	7,500
Incline Creek	5,800	3,910	5,000	6,900

[1] From Moore (1968, p. 29–33), assuming runoff as the average of runoffs indicated for zones D and S_1 of Moore's report.



Estimates of sediment transport
[Upper number, tons; lower number (in parentheses), tons per acre-foot of runoff]

Stream	1970	1971	1972	1973	4-year total (rounded)
First Creek	200	780	82	710	1,800
	(0.222)	(0.857)	(0.178)	(1.014)	(0.60)
Second Creek	1,400	3,000	490	1,700	6,600
	(1.077)	(2.00)	(0.620)	(1.545)	(1.40)
Wood Creek	960	390	20	690	2,100
	(0.480)	(0.299)	(0.027)	(0.575)	(0.38)
Third Creek	4,900	5,200	740	4,400	15,000
	(0.746)	(0.736)	(0.193)	(0.721)	(0.64)
Incline Creek	2,900	1,500	150	1,300	5,800
	(0.424)	(0.233)	(0.039)	(0.255)	(0.26)
Total	10,000	11,000	1,500	8,800	31,000
(rounded)	(0.57)	(0.52)	(0.16)	(0.62)	(0.53)

Figure 6. Comparisons of drainage areas, runoff, and sediment loads of principal streams during study period.

p. 10–11). Diversions during the irrigation season coincide to some degree with normal medium- to low-flow periods of Third Creek. Therefore, the diversions not only decrease annual runoff of Third Creek to Lake Tahoe but also reduce flow rates of the creek where the data were gathered to develop the flow-duration curve. Diversions during periods of high streamflow have a negligible effect on the curve.

Comparisons with Generalized Regional Runoff

Variations in runoff of individual streams during the study period and in the cumulative runoff of all streams from year to year are shown in table 3. However, the tabular data do not provide any perspective on the relations between runoff characteristics of individual study-period years and short- or long-term runoff throughout the region. Each year, the U.S. Soil Conservation Service summarizes regional snowmelt runoff. The Service compared April-September runoff, which includes the bulk of the annual snowmelt runoff, with that of the same period for the previous 15 years. The U.S. Soil Conservation Service's summaries for the Lake Tahoe basin are as follows (U.S. Soil Conservation Service, 1970, p. 1; 1971, p. 1; 1972, p. 3; 1973, p. 1, 3): 1970, 94 percent of average; 1971, 148 percent; 1972, 76 percent; and 1973, 93 percent. The data of table 3 show cumulative runoff of the five principal streams of the study area to be equal during 1970 and 1971; this equality of runoff is contrary to the general regional runoff described by the U.S. Soil Conservation Service. In 1971, Incline and Wood Creeks show less runoff than in 1970; this decrease is also contrary to the regional trend. First, Second, and Third Creeks, however, show increased flows in 1971, thereby tending to conform more with regional conditions.

The data from tables 3 and 5 suggest that Incline Village streamflows in 1972 were generally between one-half and two-thirds of the long-term average; these streamflows are less than the 76-percent-of-normal rating that the U.S. Soil Conservation Service assigned to the overall Tahoe basin for that year. However, 1973 flows were probably about 90 percent of the long-term average, and these flows agree reasonably well with the overall Tahoe basin assessment given for that year by the U.S. Soil Conservation Service.

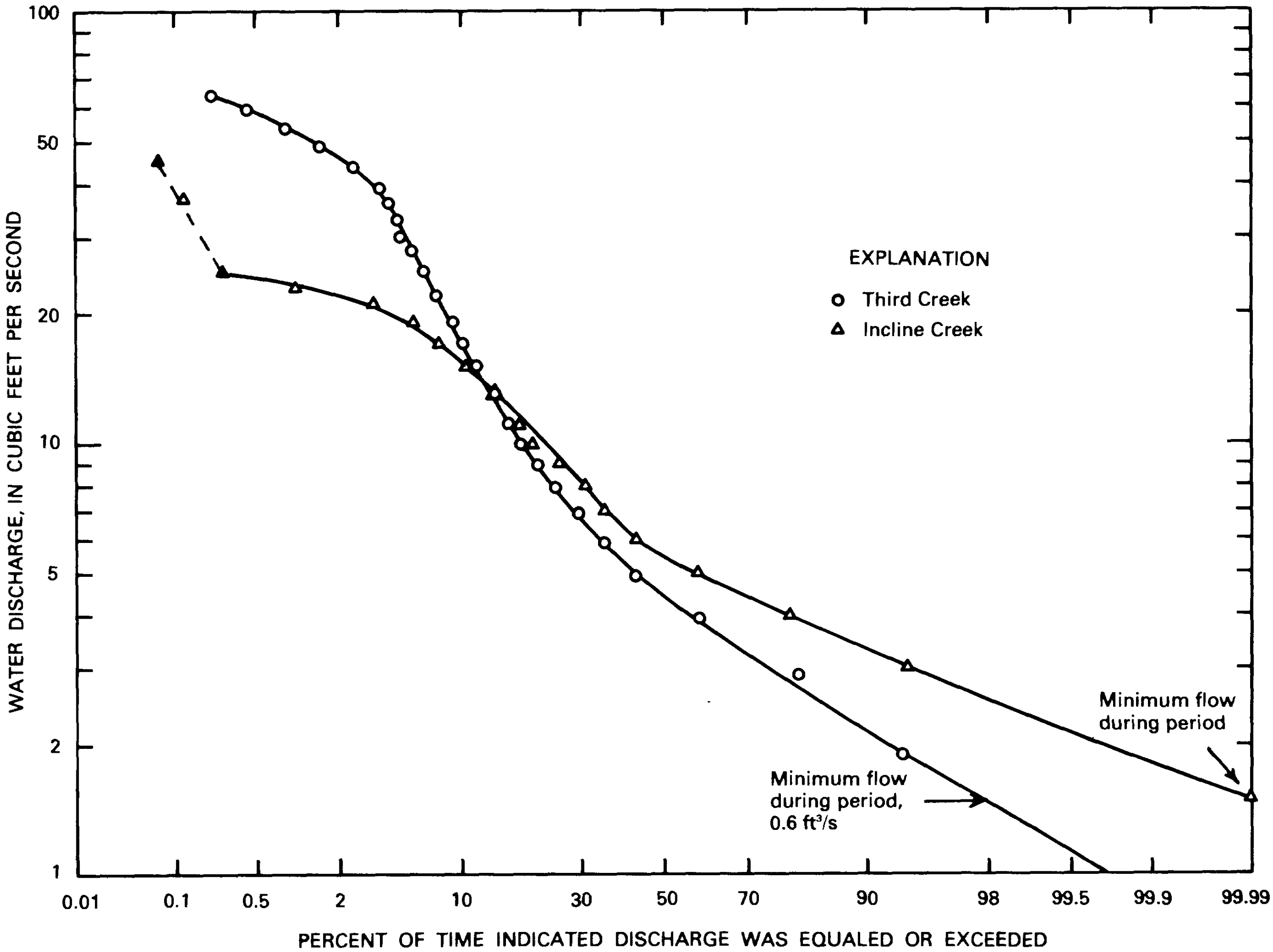


Figure 7. Flow duration curves of Third and Incline Creeks near their mouths, water years 1970–73.

Specific Conductance and Water Temperature of Runoff

Specific-conductance[1] and water-temperature data provide an index of general stream-water quality. Such data, obtained concurrently with almost all sediment samples collected during this study, are tabulated in the published progress reports (Glancy, 1971, 1973, 1976a, b).

Measured specific conductances of principal Incline Village streams near their mouths ranged as follows:

Stream	Specific conductance (µmho)
First Creek	38–344
Second Creek	32–136
Wood Creek	35–99
Third Creek	23–113
Incline Creek	37–284

The conductance data also showed the following characteristics: (1) All tributaries to Lake Tahoe from the study area are generally dilute with respect to dissolved-solids concentration. (2) Dissolved-solids concentrations of perennial creeks fluctuate seasonally and are greater during low-flow periods and less during peak snowmelt runoff. (3) The initial storm runoff of autumn appears to mobilize soluble salts that have accumulated during the preceding summer low flow. (4) Runoff of snowmelt from developed areas occasionally shows short-duration surges

[1]The dissolved-solids concentration of water, in milligrams per liter, is generally about two-thirds of the specific conductance value, in micromhos per centimeter at 25 °C (hereafter shortened to "micromhos" (µmho)).

of increased salinity, probably caused by runoff from roadways that were salted to melt ice. (5) Except for the occasional effects of road salt, conductances generally did not exceed 90 μmho.

Streamflow temperature data showed not only the effects of warm summer air temperatures on stream temperatures but also the cooling influence of winter air temperatures and snowmelt runoff on the temperatures of perennially flowing streams. The data might be used to characterize the temperature environments of the creeks in the developed areas, but a detailed analysis is beyond the scope of this study.

SEDIMENT TRANSPORT

A proper understanding of the relation of erosion to the status of Lake Tahoe water quality requires knowledge of fluvial-sediment transport in the lake basin. This report section summarizes a variety of sediment-transport data and provides a basis for understanding sediment transport and its relation to urbanization for the Incline Village area.

Sediment Discharges, Loads, and Concentrations of Principal Drainages

Annual sediment discharges of the principal drainages to the lake are summarized in figure 6, which also shows the relation of sediment discharges to drainage areas and runoff. Third Creek, which constitutes only 34 percent of the cumulative five-stream drainage area, contributed about 40 percent of the study-period runoff and about 48 percent of the sediment to Lake Tahoe (fig. 6); Second Creek, with only 9 percent of the tributary drainage area and 8 percent of the runoff, delivered 21 percent of the sediment to Lake Tahoe. In addition to their disproportionate water and sediment discharges, Second and Third Creeks have at least one other hydrologic characteristic in common; both creeks experienced severe thunderstorm-related flash floods in recent years. Third Creek flooded in August 1965, and Second Creek in August 1967 (Glancy, 1969). These debris-charged floods caused major changes in the channel characteristics of the two creeks, particularly in main-stem channels. The changes upset the sediment-transport equilibria and therefore will continue to affect runoff-sediment transport relations until natural processes establish new equilibrium conditions. The above-average discharges of sediment from Second and Third Creeks, compared to discharges of other drainages, are caused in large part by the diminishing, but still lingering, effects of these recent floods. The normally intense runoff characteristics of Third Creek, discussed in the Runoff Characteristics of Principal Drainage Basins section of this report, undoubtedly also influenced the above-normal sediment contribution of Third Creek.

Wood Creek, on the other hand, is characterized by lower-than-average contributions of runoff and sediment for its drainage area. The very low proportion of sediment transport by Incline Creek for its drainage area is also conspicuous.

In figure 6, the combined annual sediment discharges and runoff are further described by numerically weighting tons of sediment load against runoff. The annual totals of figure 6 show 1972 as the abnormal study year, and a comparison of the 1972 total with those of other years again dramatizes the exponential relation between runoff and sediment transport.

Figure 8 logarithmically depicts approximate relations between annual sediment discharge and annual runoff for each of the five principal Incline Village Creeks during the study period. The vertical separation between the individual stream graphs appears generally related to differences in drainage area sizes of the different creeks; that is, curves for the larger drainages are located above curves of the smaller drainages. Although each curve is loosely defined, their similar slopes suggest some similarity in sediment transport throughout the study area. The figure includes a curve depicting the relation between annual runoff and sediment transport for the composite five-stream Incline Village drainage group. That curve, as expected, has a slope similar to the other curves.

For comparison, figure 8 includes a curve for Glenbrook Creek (fig. 1), based on data for the 1972–74 water years. Although the magnitudes of annual sediment loads of Glenbrook Creek are dramatically less than those of Incline Village creeks (Glancy, 1977), the approximate slope of the water-sediment transport relation curve for Glenbrook Creek is similar to those of the Incline Village creeks. The Glenbrook Creek curve is also in the proper general vertical position with regard to its drainage area size, when compared to the five Incline Village creeks.

Nearly 2,000 sediment samples collected mainly near the mouths of the five principal tributaries were statistically analyzed to evaluate relations between streamflow and sediment transport. Five key variables were test-correlated to assess degrees of linear relations between the variables. Water discharge was assumed to be the independent variable and was compared with (1) total sediment concentration, (2) total sediment load, (3) coarse-grained sediment load, and (4) fine-grained sediment load. Linear regressions were tested according to three data modes: arithmetic, semilogarithmic, and logarithmic. The tests suggested that logarithmic transformations of the data resulted in the highest linear correlations of the variables; thus, log-data transformations were selected to compare data from the different streams and sites.

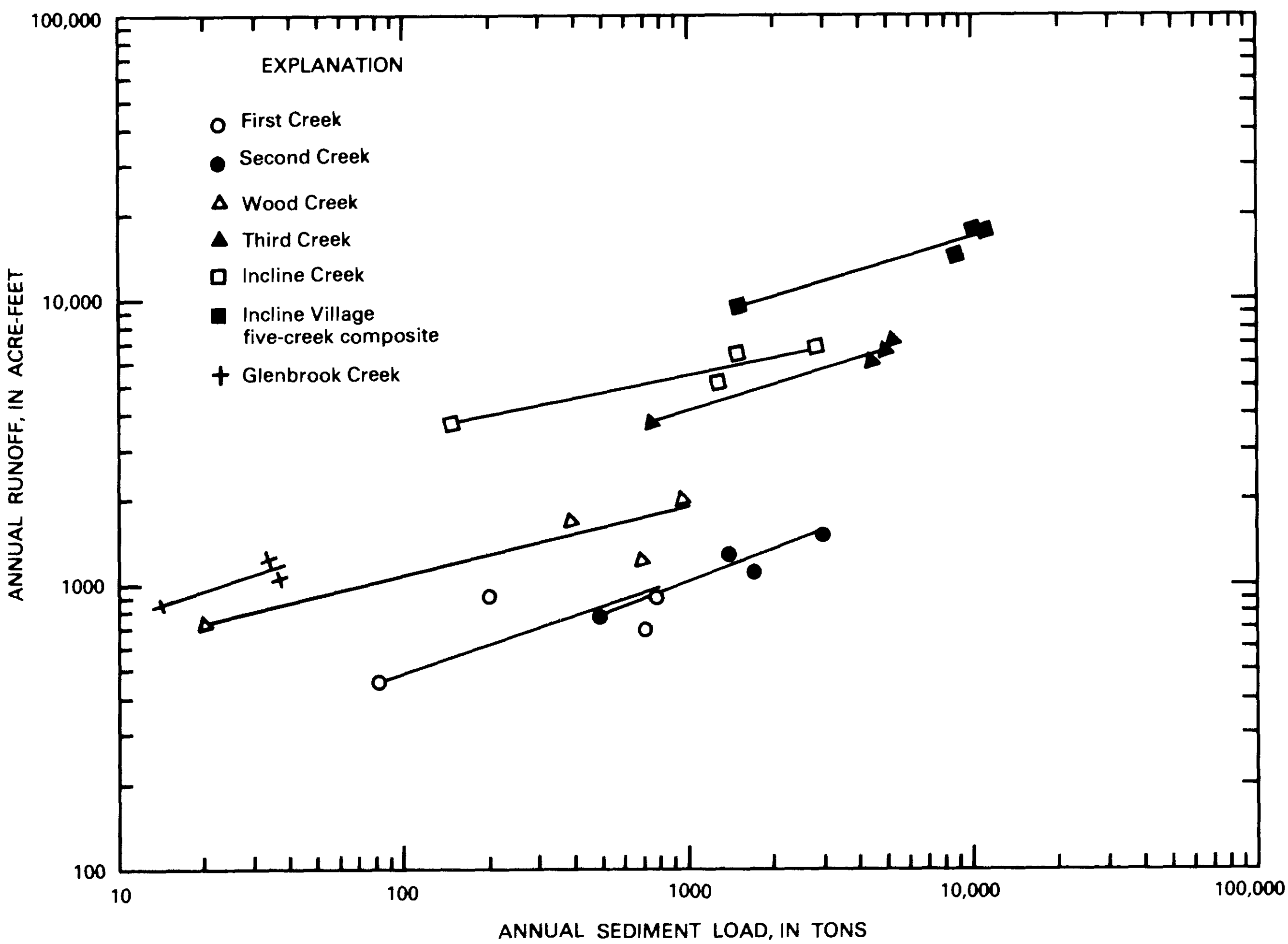


Figure 8. Relation of total annual runoff to sediment load for the principal Incline Village streams and for Glenbrook Creek.

Results of the linear-regression analyses performed on logarithmic data transformations are summarized in table 6. A comparison of correlation coefficients for relations between water discharge and total sediment loads shows that Third Creek generally has the best correlations (largest coefficients); Wood, Second, and Incline Creeks are slightly lower; and First Creek shows much poorer correlations (smallest coefficients). The magnitudes of standard errors of estimate of the dependent variables indicate that sizable errors are likely if the regression equations are used to predict sediment loads on the basis of known water discharges.

Correlation coefficients between water discharge and coarse- and fine-grained sediment loads show that coarse-grained loads (mean particle diameters equal to or greater than 0.062 mm, or coarser grained than silt) generally correlate much better with water discharge than do fine-grained loads (particle diameters smaller than 0.062 mm, or finer grained than sand).

The magnitudes of regression-equation exponents predict rates of change in magnitudes of the dependent variables that accompany changes of the independent variable (larger exponents imply greater rates); specifically, the exponent value defines the slope of the regression line on a logarithmic graph of the data. The exponent value is an indicator of the sensitivity of the dependent variable in response to changes of the independent variable; the larger the exponents, the greater the sensitivity.

The exponents for equations in table 6 generally suggest that, for total-study-period data, changes in sediment concentrations and total loads of First Creek were less sensitive to water-discharge changes than those of other creeks. First Creek also shows the greatest range in exponents (1.0–3.2) on year-by-year analyses of the data, and Second Creek has the lowest range (2.4–2.7). A comparison of exponents also shows that coarse-grained sediment loads of all creeks near their mouths were much more sensitive to changing water discharge than were fine-grained sediment loads. Coarse- and fine-grained sediment loads appeared equally sensitive to water-discharge changes for Third Creek above the developed area, but those relations were defined by only a small number of data and are therefore probably less accurate than relations for the other sites.

Table 6. Summary of linear-regression analyses of sediment-transport data

[Independent variable, water discharge (Q_w); dependent variables, sediment concentration (C_s) and sediment discharge (Q_s)]

Stream[1]	Number of data points	Correlation coefficient	Regression equation	Standard error of estimate of dependent variable (log units)
Total study period				
Total sediment concentration (C_s)				
First Creek	299	0.37	$C_s=150Q_w^{0.85}$	0.70
Second Creek	320	.73	$C_s=100Q_w^{1.6}$	.55
Wood Creek	316	.79	$C_s=13Q_w^{1.7}$	.48
Third Creek, ADA	196	.83	$C_s=1.5Q_w^{1.4}$	.44
Third Creek, NM	464	.77	$C_s=5.7Q_w^{1.5}$	.50
Incline Creek	416	.71	$C_s=2.1Q_w^{1.8}$	.48
Total sediment discharge (Q_{st})				
First Creek	292	0.63	$Q_{st}=0.49Q_w^{1.6}$	0.66
Second Creek	319	.87	$Q_{st}=0.29Q_w^{2.5}$	.54
Wood Creek	310	.89	$Q_{st}=0.035Q_w^{2.7}$	.48
Third Creek, ADA	196	.93	$Q_{st}=0.0042Q_w^{2.4}$	.43
Third Creek, NM	464	.90	$Q_{st}=0.016Q_w^{2.5}$	.50
Incline Creek	416	.84	$Q_{st}=0.0056Q_w^{2.8}$	.48
Coarse-sediment discharge (Q_{sc})				
First Creek	24	0.58	$Q_{sc}=0.54Q_w^{1.9}$	0.70
Second Creek	30	.77	$Q_{sc}=0.65Q_w^{1.9}$	.52
Wood Creek	16	.84	$Q_{sc}=0.006Q_w^{3.7}$	.36
Third Creek, ADA	6	.94	$Q_{sc}=0.045Q_w^{1.4}$	.21
Third Creek, NM	51	.88	$Q_{sc}=0.041Q_w^{2.2}$	.43
Incline Creek	34	.78	$Q_{sc}=0.0068Q_w^{2.7}$	.47
Fine-sediment discharge (Q_{sf})				
First Creek	25	0.18	$Q_{sf}=1.48Q_w^{0.48}$	0.67
Second Creek	31	.55	$Q_{sf}=1.60Q_w^{0.87}$	.46
Wood Creek	17	.51	$Q_{sf}=0.79Q_w^{1.4}$	.51
Third Creek, ADA	6	.94	$Q_{sf}=0.45Q_w^{1.4}$	.21
Third Creek, NM	51	.53	$Q_{sf}=0.83Q_w^{0.82}$	.49
Incline Creek	34	.41	$Q_{sf}=0.48Q_w^{1.2}$	.57
1970 water year				
Total sediment discharge (Q_{st})				
First Creek	45	0.85	$Q_{st}=0.15Q_w^{2.4}$	0.52
Second Creek	52	.82	$Q_{st}=0.24Q_w^{2.5}$	.62
Wood Creek	59	.86	$Q_{st}=0.056Q_w^{2.8}$	.57
Third Creek, ADA	34	.91	$Q_{st}=0.0055Q_w^{2.4}$	.45
Third Creek, NM	52	.91	$Q_{st}=0.0090Q_w^{2.8}$	.53
Incline Creek	80	.87	$Q_{st}=0.0074Q_w^{2.8}$	.47
1971 water year				
Total sediment discharge (Q_{st})				
First Creek	111	0.51	$Q_{st}=0.63Q_w^{1.4}$	0.72
Second Creek	114	.89	$Q_{st}=0.25Q_w^{2.7}$	.54
Wood Creek	114	.91	$Q_{st}=0.037Q_w^{2.5}$	.41
Third Creek, ADA	73	.94	$Q_{st}=0.0056Q_w^{2.3}$	.42
Third Creek, NM	167	.88	$Q_{st}=0.067Q_w^{2.1}$	.48
Incline Creek	151	.76	$Q_{st}=0.017Q_w^{2.4}$	.49
1972 water year				
Total sediment discharge (Q_{st})				
First Creek	73	0.76	$Q_{st}=0.58Q_w^{3.2}$	0.48
Second Creek	87	.79	$Q_{st}=0.32Q_w^{2.4}$	.53
Wood Creek	71	.69	$Q_{st}=0.035Q_w^{1.8}$	.47
Third Creek, ADA	51	.92	$Q_{st}=0.0013Q_w^{2.9}$	.43
Third Creek, NM	123	.93	$Q_{st}=0.0054Q_w^{2.8}$	.42
Incline Creek	95	.79	$Q_{st}=0.0027Q_w^{2.9}$	.42

Table 6. Summary of linear-regression analyses of sediment-transport data—Continued

[Independent variable, water discharge (Q_w); dependent variables, sediment concentration (C_s) and sediment discharge (Q_s)]

Stream[1]	Number of data points	Correlation coefficient	Regression equation	Standard error of estimate of dependent variable (log units)
1973 water year				
Total sediment discharge (Q_{st})				
First Creek	63	0.51	$Q_{st}=1.11Q_w^{1.0}$	0.58
Second Creek	66	.89	$Q_{st}=0.36Q_w^{2.4}$	.48
Wood Creek	66	.94	$Q_{st}=0.030Q_w^{2.9}$	.39
Third Creek, ADA	38	.95	$Q_{st}=0.0060Q_w^{2.3}$	.39
Third Creek, NM	93	.93	$Q_{st}=0.0098Q_w^{2.5}$	.44
Incline Creek	90	.87	$Q_{st}=0.0092Q_w^{2.6}$	.43

[1] Principal data-collection sites as shown in figure 1, except Third Creek, ADA, which is supplementary site located just above development area. Third Creek, NM, is the principal site, near mouth.

Relations between instantaneous sediment transport and runoff for two of the principal measurement sites of the study area are graphically described in figures 9 and 10. The graphs include all sediment-load data collected for which concurrent sediment particle-size distribution data also were obtained at the principal measurement sites of Third and Incline Creeks, the two major drainages. The figures include the results of linear-regression analyses of the data and thus provide visual perspective to the results of the statistical-data analyses. Figures 9*A* and 10*A* show the general relations between water discharges and total-sediment loads for Third and Incline Creeks near their mouths. Specifically, increasing water discharges are generally accompanied by increasing sediment loads and vice versa. However, because of the appreciable scatter of data points that roughly define the general trends, the data define no single regression line or equation that would allow an accurate estimate of sediment-load movement solely on the basis of known water discharge at either of the two sampling sites. Figures 9*B* and 10*B* show that the relations between movement of the coarse-grained fraction of the total sediment load (sand and gravel) and water discharge were generally as well defined, or slightly better defined, as those between total load and water discharge. In contrast, figures 9*C* and 10*C* show that changes in the fine-grained sediment component (silt and clay fraction) of the total load were poorly related to changing water discharge at the two measurement sites.

The time relations between runoff and sediment discharge were derived by using the flow-duration curves of figure 7. Daily sediment discharge was cumulated through varying ranges of daily-mean water discharges to determine sediment-transport rates. The results showed that Incline Creek moved about 28 percent of its sediment during the 1 percent of the study period characterized by highest daily-flow rates and about 66 percent during the 10 percent of the study period characterized by highest daily-flow rates. Likewise, Third Creek moved about 31 percent and 85 percent of its load during 1 percent and 10 percent of the time, respectively. Thus, Third Creek appears flashier than Incline Creek with respect to sediment transport, as it does with regard to water discharge (see Runoff section).

The much greater transport of sediment by snowmelt runoff, compared to combined rainfall and low-flow runoff, is shown in figure 11. About 90 percent of the total cumulative study-period sediment transport to the lake took place during periods of snowmelt runoff.

Table 7 summarizes observed minimum and maximum sediment-transport rates of the principal creeks near their mouths on a year-by-year basis. Measured sediment concentrations ranged from 1 mg/L to 13,200 mg/L, and sediment discharges computed from the sediment-concentration and water-discharge data ranged from 0.001 to 1,420 t/d. Maximum measured concentrations and discharges from the undeveloped areas were somewhat less than those measured near stream mouths where development is greater. Sampling was programmed to measure extreme cases of sediment transport at all sites; however, fewer samples were collected upstream than near creek mouths.

The maximum sediment concentration measured during the study was 62,300 mg/L in flow from a small utility road to Second Creek (Glancy, 1976b, p. 6) (see fig. 17). However, in spite of the high concentration, the sediment-transport rate was only 50 t/d at the instant of the measurement because concurrent water discharge was only about 0.3 ft^3/s. Numerous other sediment concentrations greater than 10,000 mg/L also were measured during the course of the study; however, these high concentrations were noted mainly in minor tributaries, gutters, or drains and at times when water discharge rates were relatively low compared to those common to the perennially flowing channels.

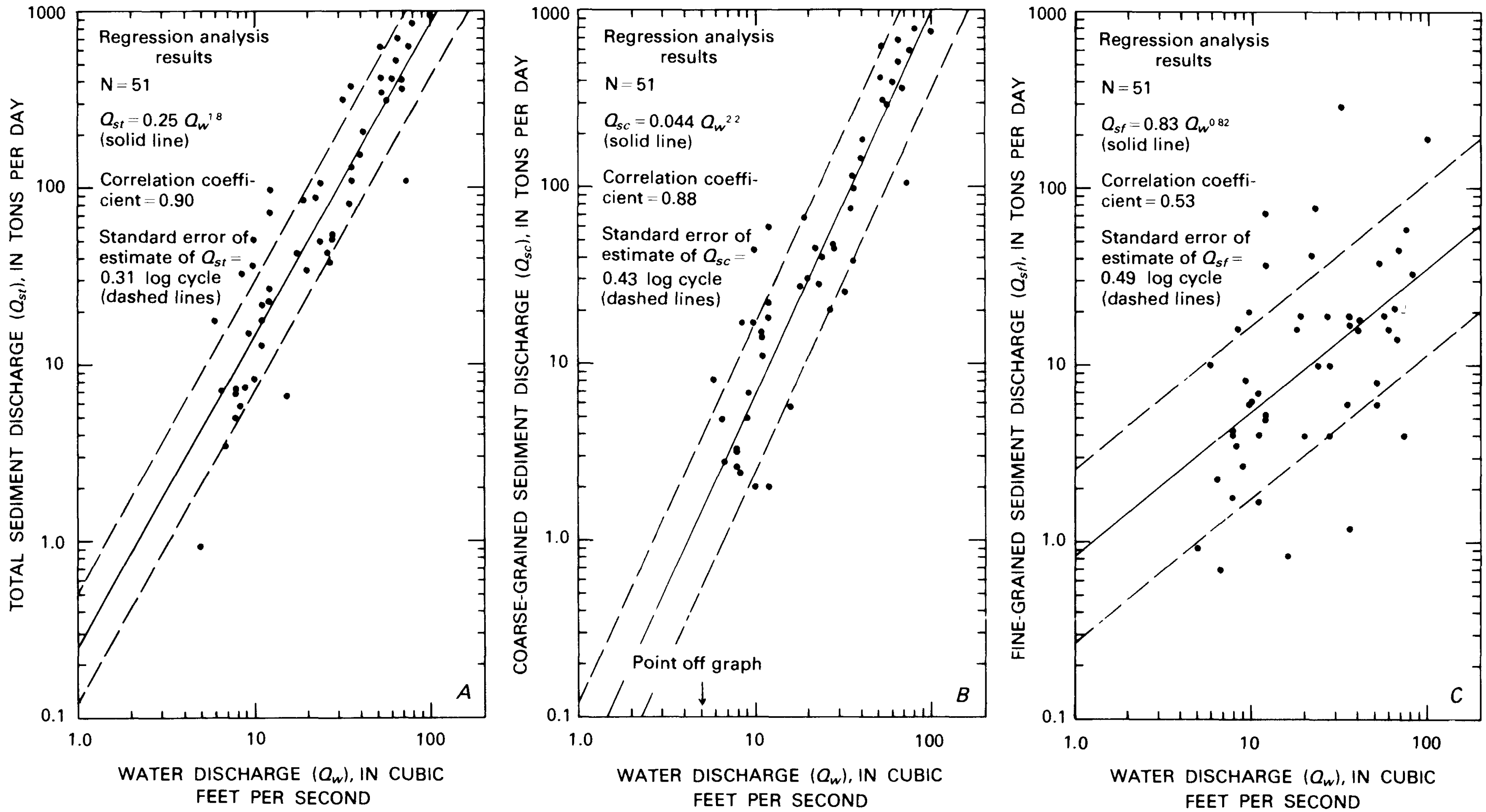


Figure 9. Relation of water discharge to *A*, total sediment discharge; *B*, coarse-grained sediment discharge; and *C*, fine-grained sediment discharge at times of particle-size sampling for Third Creek near its mouth.

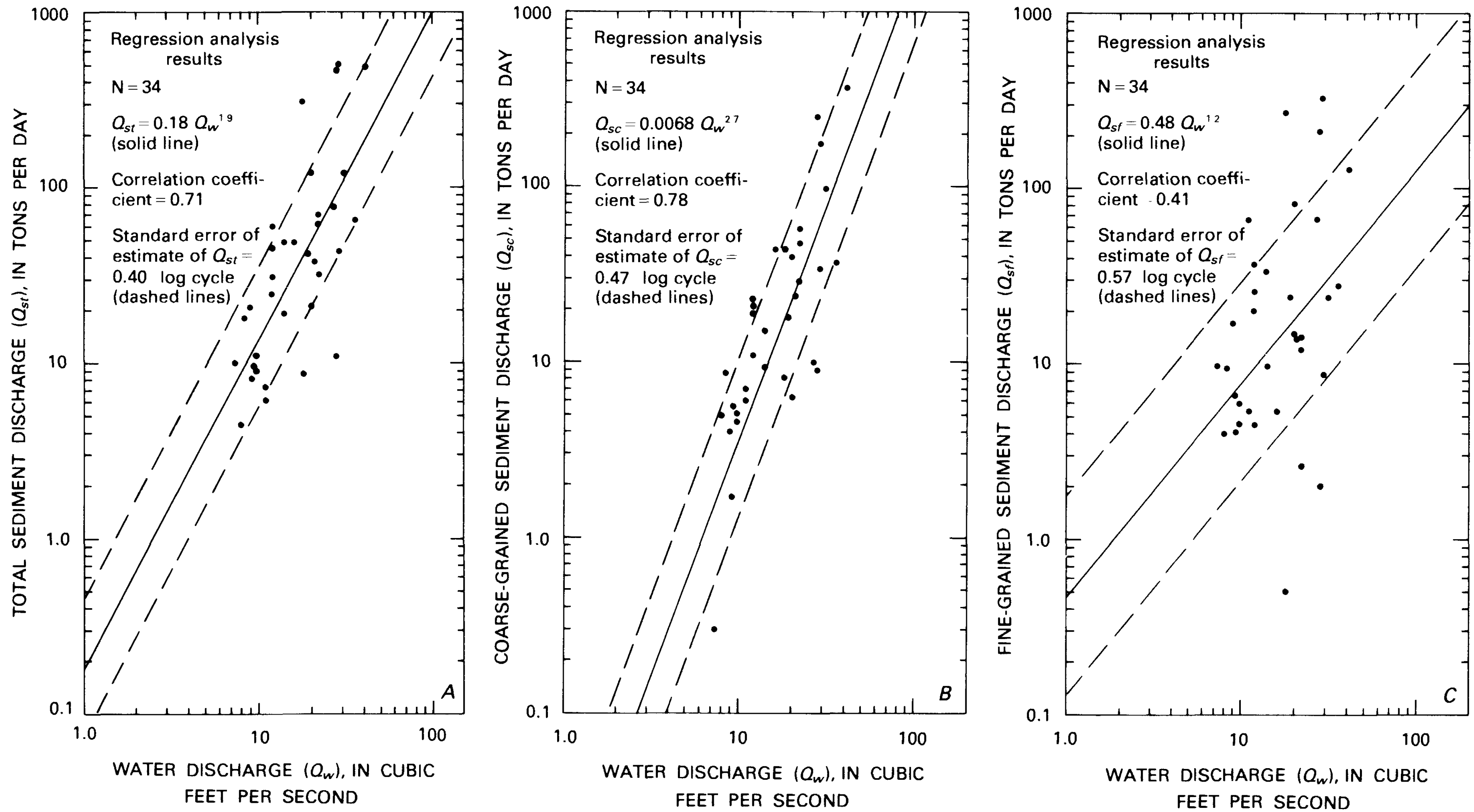


Figure 10. Relation of water discharge to *A*, total sediment discharge; *B*, coarse-grained sediment discharge; and *C*, fine-grained sediment discharge at times of particle-size sampling for Incline Creek near its mouth.

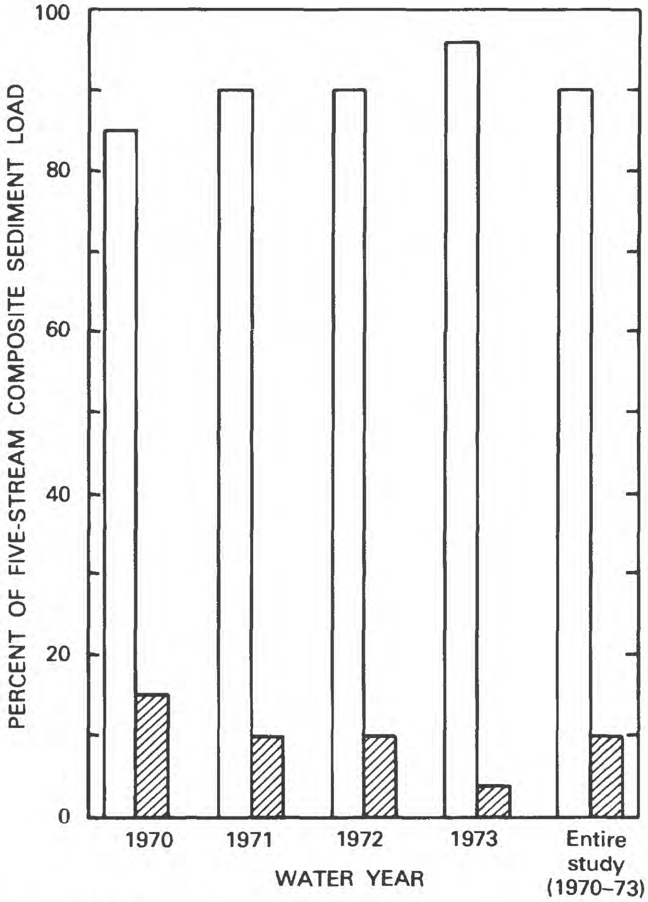


Figure 11. Approximate distribution of sediment transport to Lake Tahoe by principal streams during snowmelt runoff (open bars) and rainfall or low-flow runoff (patterned bars).

Streamflows, sediment concentrations, and, therefore, sediment discharges can and do fluctuate greatly within a day during periods of snowmelt and rainfall runoff. A typical example of the nature of the fluctuations are those measured near the mouth of Third Creek on April 2, 1971, as follows:

Time (24-hr)	Water discharge (ft^3/s)	Total sediment concentration (mg/L)	Total sediment discharge (t/d)
0630...........	7.6	214	4.4
1410...........	8.2	639	14
1555...........	9.8	1,890	50
1720...........	10	661	18
Mean daily...	7.6	400	8

This tabulation shows that measured sediment concentration increased by almost 9 times and that sediment discharge increased by about 11 times within approximately 9 hours (0630 to 1555 hours), while water discharge increased only about 30 percent. During the almost 2 hours between 1555 and 1720 hours, sediment concentration and discharge decreased by about two-thirds, while water discharge continued to increase slightly. This example demonstrates some of the daily complexities of water-sediment relations during snowmelt runoff.

Some common, but important, relations among water discharge, sediment transport, and runoff characteristics are better appreciated and understood by comparing quantitative hydrologic data for specific flow situations in conjunction with photographs of streamflow conditions at the time of data collection. Figure 12 shows examples of three radically different types of runoff as viewed from the same vantage point near the mouth of Third Creek. Measured hydrologic data corresponding to the runoff conditions shown in figure 12 are as follows:

Date	Approximate water discharge (ft^3/s)	Approximate total sediment concentration (mg/L)	Approximate total sediment discharge (t/d)	Sediment particle-size distribution (percent)		Runoff character
				Sand, gravel	Silt, clay	
Mid-August.. 1971	3.5	7	0.1	Unknown		Seasonal low flow.
December... 21, 1969	23	1,700	100	26	74	Rainfall runoff.
June 17, ... 1971	65	4,000	700	97	3	Snowmelt runoff.

A comparison of figure 12*A* with its corresponding data shows that the flow is small and clear and that sediment transport is minimal. Similar comparisons of 12*B* and 12*C* suggest that water discharge on June 17, 1971, is greater than that of December 21, 1969, but the magnitude of the difference is difficult, or impossible, to accurately discern. Likewise, precise differences in water discharge among all photographed scenes are impossible to determine without flow-measurement data. The relatively high percentage (74 percent) of fine-grained sediment (silt and clay) suspended in the flow shown in 12*B* caused the high turbidity that visually suggests an incorrect impression of greater sediment transport on December 21, 1969, than on June 17, 1971. In contrast, the low fine-grained sediment content (3 percent) of June 17, 1971, creates a false impression that the sediment discharge is relatively small, when in fact it is over twice as concentrated and 7 times greater than that of December 21, 1969. The folly of trying to visually assess sediment transport to any reasonable degree of accuracy is apparent from this example.

Total-Sediment Transport Versus Suspended-Sediment Transport

As discussed in the section Data Collection and Analysis, the total-sediment transport measurements applied in this study are not typical of most sediment

Figure 12. Third Creek near its mouth, *A*, during mid-August 1971; *B*, on December 21, 1969; and *C*, on June 17, 1971.

Table 7. Summary of measured instantaneous sediment-transport extremes of principal streams near their mouths
[Sediment concentrations in milligrams per liter; sediment discharges in tons per day]

Stream	1970 water year				1971 water year			
	Concentration		Discharge		Concentration		Discharge	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
First Creek	1	1,900	0.001	19	4	13,200	0.01	103
Second Creek	4	3,500	.01	80	5	10,200	.01	158
Wood Creek	4	6,800	.01	94	3	1,360	.01	35
Third Creek[1]	3	3,670	.04	408	7	5,660	.07	1,420
Incline Creek[2]	4	6,470	.06	625	9	4,400	.14	178

Stream	1972 water year				1973 water year			
	Concentration		Discharge		Concentration		Discharge	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
First Creek	3	1,900	0.003	5.6	2	6,780	0.002	26
Second Creek	5	2,460	.008	20	1	4,440	.002	126
Wood Creek	2	207	.003	2.0	2	2,080	.004	55
Third Creek[1]	2	1,410	.006	137	2	5,630	.01	912
Incline Creek[2]	3	861	.02	23	5	2,320	.05	169

[1] Measured concentrations from undeveloped areas ranged from less than 1 to 1,390 mg/L, and measured discharges ranged from less than 0.01 to 454 t/d during study period.
[2] Measured concentrations from undeveloped areas ranged from 1 to 565 mg/L, and measured discharges ranged from less than 0.01 to 9 t/d during study period.

transport investigations. Therefore, during the course of this study, a reconnaissance was made to determine the possible relations of total-load transport to suspended-load transport. Only one measurement site was investigated in this regard. Third Creek near its mouth was chosen because data for 1970 and 1971 water years (fig. 6) suggested Third Creek as the major source of sediment to Lake Tahoe within the study area. Therefore, knowledge of the relations between suspended- and total-sediment transport at this site is probably more significant than at any other known site in the area. Twenty-five samples were collected for suspended-sediment analysis concurrently with samples for total-sediment analysis during the 1972 water year, and 37 samples were collected during the 1973 water year. The 1972 dual-data collection program took place during the period of most intensive snowmelt runoff, coincident with the anticipated period of greatest sediment transport, as dictated by 1970 and 1971 analytical results. The dual-sampling schedule was broadened during 1973 to include a few data for rainfall-runoff events and for the periods of less intensive snowmelt runoff.

Independent analyses of the suspended-sediment data and the total-sediment data for periods of dual-data collection indicated that, cumulatively, suspended-sediment loads were about one-fourth of total loads. The number of dual data sets was insufficient to guarantee that suspended loads were consistently only one-fourth of the total loads; however, the results strongly suggest that suspended-sediment loads make up only a minor part of the total loads at this important data-collection site.

Suspended-total load relations may be similar to the Third Creek relations for most of the other sampling sites in the study area. This belief is based, in part, on similarities between sampling-site characteristics and particle-size distributions of sediment moving in Third Creek and those of the other four major tributaries, as described in the next section of this report.

Particle-Size Distribution of Sediment Discharges

The assessment of particle-size distribution of sediment discharged to Lake Tahoe is helpful in understanding the complex effects of erosion, fluvial-sediment transport, and sediment deposition on the lake-basin environment. The sediment-transport problems are dependent not only on the magnitude and timing of sediment movement but also on the character of material being eroded, moved, and deposited. Some examples of particle-size related effects are (1) fine-grained sediment deposition in stream channels clogs streambed gravels and affects life processes of the streambed-dwelling biota; (2) very fine grained sediment transport causes turbid streamflow that may be esthetically unpleasant and that also affects light transmittance, thereby influencing algal growth rate; (3) coarse-grained sediments abrade parts of the channel during transit, thereby increasing erosion potential and altering the stream-channel environment;

(4) different particle sizes have different mineralogical composition, exhibit different electrochemical surface characteristics, and therefore have different effects on the release and uptake of various chemical constituents in both transporting and receiving water; and (5) different particle sizes have different physical effects in near-shore lake depositional areas (for example, fine-grained particles affect lake turbidity while in suspension, and coarse-grained particles tend to build deltas and beaches, fill in boat harbors, and bury existing deposits that may have been more or less harmful to the lake environment).

Particle-size ranges of various size classes, after Lane and others (1947, p. 937), are as follows (—means number was too large to record):

Sediment-size class	Diameter range		
	Millimeters	Micrometers	Inches
Boulders	260–4,100	—	10–160
Cobbles	64–260	—	2.5–10
Gravel	2.0–64	—	0.078–2.5
Sand	0.062–2.0	62–2,000	0.0024–0.078
Silt	0.0040–0.062	4.0–62	0.00015–0.0024
Clay	0.00024–0.0040	0.24–4.0	0.000010–0.00015

Estimated particle-size distributions of sediment discharges to Lake Tahoe by the five principal creeks of the study area are summarized, by tonnages and percentages, in table 8. Table 8 shows that the combined sand-gravel component makes up the dominant fraction of sediment discharged to the lake. Clay-size sediment makes up the smallest proportion of annual and cumulative study-period sediment transport. Composition of the 4-year, five-stream cumulative sediment discharge to Lake Tahoe was approximately 75 percent gravel and sand, 15 percent silt, and 10 percent clay.

Insufficient particle-size data were available to differentiate gravel from the combined sand-gravel component of annual sediment discharges of the various streams; however, available data strongly suggested that, overall, quantities of sand generally exceeded those of gravel. The following information and conclusions on gravel transport were deduced from sample data and field observations.

In all particle-size samples collected near the mouths of the five principal streams, gravel was usually less than 25 percent and commonly less than 15 percent. The maximum amount of gravel encountered in any given sample was 38 percent of the total load in a 1971 Third Creek sample. Therefore, gravel probably composed only a minor part of the combined gravel-sand component of annual and cumulative study-period sediment discharges of the five streams to the lake.

Only once was cobble-size (64-mm) particle movement noted. On June 17, 1971, small cobbles of up to about 75-mm average-diameter size were seen moving near the mouth of Third Creek. They were not moving in great quantity, and the total tonnage transported probably made up only a small fraction of the total sediment load of Third Creek that day. More cobbles may have moved on other days during the same period of intensive snowmelt runoff, but additional movement was not observed during the many sampling periods.

Particle sizes greater than 8-mm sieve-diameter size (fine gravel) were neither observed moving nor sampled in First, Third, Wood, or Incline Creeks. On two occasions, once each in the 1970 and 1971 water years, Second Creek samples contained particles in the 8-mm to 16-mm sieve-diameter size range. All other Second Creek particle-size samples were composed of sediment less than 8 mm in diameter.

As shown in table 8, the sand-and-gravel fractions were greatest during 1973 in all streams. This may be the result of landscape stabilization through time, resulting in decreasing erosivity, in residential subdivisions constructed during early years of the study. The landscape stabilization process, if operative, should be accompanied by a general decrease in availability of fine-grained sediment for transport, and a probable resultant coarsening of overall sediment discharges of affected streams. Lower percentages of sand and gravel discharges of Third and Incline Creeks in 1972 than in 1971 probably are partly the result of considerably lower peak-streamflow rates, and correspondingly lower velocities, during that low runoff year.

Table 8 shows a great tonnage increase in sand-gravel discharge by First Creek during 1971 compared to 1970, but a decrease in sand-gravel percentage. The percentage decrease (or, conversely, the increase of silt and clay) is probably the result of new subdivision development in that drainage basin, built after the 1970 snowmelt runoff (fig. 4 and table 2). Second Creek drainage, also the scene of new development during 1970–71, experienced not only great increases in sand-gravel discharges in 1971 but also in sand-gravel percentages. New subdivision development was underway in the Wood Creek drainage when the study began (fig. 4 and table 2). The general proportionate increase of the sand-gravel fraction in Wood Creek throughout the study period may reflect a progressive decrease-of-erosivity trend in that basin with time.

Silt discharges of Wood, Third, and Incline Creeks decreased sharply in 1971, compared to 1970. This decrease is probably the immediate result of decreasing erosivity through time when unpaved roads, in subdivisions that were undergoing construction during the rainfall and snowmelt runoff of 1970, were largely sealed over before the start of the 1971 runoff year. This silt decrease also is reflected in percentage component drops of Third and Incline Creeks but not in that of Wood Creek. Silt

Table 8. Estimated particle-size distribution of sediment transported to Lake Tahoe by principal streams

[Lateral and vertical summations may not precisely agree because of rounding. Likewise, cumulative tonnages for individual creeks and study-area totals may not precisely agree with data in figure 6 and table 9. Loads in tons, rounded; percentages in parentheses]

Stream	1970 water year			1971 water year			1972 water year			1973 water year			4-year study period			
	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Total (rounded)
First Creek.....	140	30	30	410	190	180	51	18	14	550	100	60	1,200	340	280	1,800
	(70)	(15)	(15)	(53)	(24)	(23)	(61)	(22)	(17)	(77)	(14)	(9)	(66)	(19)	(15)	
Second Creek...	810	350	240	2,300	440	300	370	65	55	1,300	180	180	4,800	1,000	780	6,600
	(58)	(25)	(17)	(76)	(14)	(10)	(76)	(13)	(11)	(78)	(11)	(11)	(73)	(15)	(12)	
Wood Creek....	550	220	190	250	90	50	13	4	3	520	95	80	1,300	410	320	2,000
	(57)	(23)	(20)	(64)	(23)	(13)	(65)	(20)	(15)	(75)	(14)	(11)	(64)	(20)	(16)	
Third Creek....	3,800	730	350	4,500	440	270	570	95	75	3,900	320	150	13,000	1,600	840	15,000
	(78)	(15)	(7)	(86)	(9)	(5)	(77)	(13)	(10)	(89)	(7)	(4)	(84)	(10)	(6)	
Incline Creek...	1,700	740	440	990	290	220	70	40	40	1,000	180	110	3,800	1,200	810	5,800
	(59)	(26)	(15)	(66)	(19)	(15)	(46)	(27)	(27)	(78)	(14)	(8)	(65)	(21)	(14)	
Total......	7,000	2,100	1,200	8,400	1,400	1,000	1,100	220	190	7,300	880	580	24,000	4,600	3,000	31,000
(rounded)	(68)	(20)	(12)	(78)	(13)	(9)	(73)	(14)	(13)	(83)	(10)	(7)	(76)	(15)	(9)	(approx.)

component tonnages increased for both First and Second Creeks in 1971, compared to 1970, probably because of the new subdivision construction in those drainages.

Variations in clay discharges and percentage fluctuations from year to year also probably were partly related to the dynamic changes that were occurring in subdivision construction and subsequent decreasing erosivity with time.

Particle-size distribution estimates of sediment discharged to Lake Tahoe from the principal drainages by snowmelt and during periods of rainfall and low-flow runoff are listed as tonnages and percentages in table 9. The cumulative five-stream percentage estimates of annual discharges are shown in figure 13. Both table 9 and figure 13 show that the sand-gravel components are disproportionately much greater than the silt-clay components in all streams during all years, except during the rainfall and low-flow runoff of 1970. Although the largest tonnages of silt and clay move during snowmelt runoff (table 9), greater percentages of silt and clay move during rainfall and low-flow runoff (fig. 13). The sand-gravel component was particularly dominant during snowmelt runoff because (1) snowmelt runoff usually caused the highest streamflow discharges capable of mobilizing large quantities of coarse-grained sediment stored in stream channels and (2) rainfall runoff originates largely from lowland areas, because storms commonly occur as rainfall at low altitudes and snowfall at high altitudes. Most land development has occurred in the lowlands, and fine-grained sediment presumably was available for transport in greater proportions there than in undeveloped areas.

Sediment Yields

Quantitative assessment of concurrent sediment loads transported from different drainages permits quantitative comparisons of sediment yields from the different areas. However, comparisons of sediment loads from different-sized drainages require that some unit drainage-area rating system be used to minimize effects of drainage-area size. The sediment-yield rating system is used in this report to quantitatively characterize sediment movement from any given area during a specified time period and to make comparisons of sediment-movement rates between different-sized areas. Sediment yield is defined, for purposes of this report, as the annual sediment load in tons passing a specific hydrologic measuring site, divided by the contributing drainage area, in square miles, above the measurement site during a specified time period. Thus, sediment yield is quantitatively expressed in measurement units as tons per square mile per year.

The sediment-yield rating system has several weaknesses, as well as the obvious desirable features described above. The system inherently implies a uniform rate of sediment transport from a specified area during a given time period, but sediment transport rarely occurs in this manner. Sediment movement is nonuniform in space and time because the movement is governed by a variety of factors, including the availability of sediment for transport at any specific point and sufficient flow of water at that point to move it. Also, comparisons of sediment yields from considerably different-sized drainage areas are not as meaningful as comparisons of yields from like-size areas.

Drainage area is one of the key parameters governing sediment-yield calculations. Areas of urban development were determined early during the study period, by using a combination of maps less detailed than maps available in 1975. These preliminary areas were used to determine the sediment yields listed in the progress reports for this study. The quantitative estimates of developed and undeveloped areas were refined for this sum-

Table 9. Estimated particle-size distribution of sediment transported to Lake Tahoe by principal streams during periods of snowmelt, rainfall, and low-flow runoff

[Lateral and vertical summations may not precisely agree because of rounding. Likewise, cumulative tonnages for individual creeks and study-area totals may not precisely agree with data in figure 6 and table 8. Loads in tons, rounded; percentages in parentheses]

Stream	1970 water year			1971 water year			1972 water year			1973 water year		
	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay	Sand and gravel	Silt	Clay
Snowmelt runoff												
First Creek	140	20	8	400	170	160	45	14	8	510	83	43
	(83)	(12)	(5)	(55)	(23)	(22)	(67)	(21)	(12)	(80)	(13)	(7)
Second Creek	810	310	180	2,100	370	230	330	42	35	1,300	170	170
	(62)	(24)	(14)	(78)	(14)	(8)	(81)	(10)	(9)	(80)	(10)	(10)
Wood Creek	520	130	50	240	84	41	10	3	2	500	88	73
	(74)	(19)	(7)	(66)	(23)	(11)	(67)	(20)	(13)	(76)	(13)	(11)
Third Creek	3,600	570	220	4,200	310	140	560	95	75	3,800	300	140
	(82)	(13)	(5)	(90)	(7)	(3)	(77)	(13)	(10)	(90)	(7)	(3)
Incline Creek	1,600	520	200	900	230	160	57	35	32	990	160	90
	(69)	(22)	(9)	(70)	(18)	(12)	(46)	(28)	(26)	(80)	(13)	(7)
Total	6,700	1,600	660	7,800	1,200	730	1,000	190	150	7,100	800	520
(rounded)	(75)	(18)	(7)	(80)	(12)	(8)	(75)	(14)	(11)	(84)	(10)	(6)
Rainfall and low-flow runoff												
First Creek	3	9	20	6	20	20	6	4	6	44	17	17
	(9)	(28)	(63)	(13)	(43)	(44)	(38)	(24)	(38)	(56)	(22)	(22)
Second Creek	Trace	40	60	160	70	70	40	23	20	20	10	10
		(40)	(60)	(54)	(23)	(23)	(48)	(28)	(24)	(50)	(25)	(25)
Wood Creek	30	90	140	5	7	9	3	1	1	11	7	7
	(12)	(34)	(54)	(24)	(33)	(43)	(60)	(20)	(20)	(44)	(28)	(28)
Third Creek	220	160	130	260	130	130	4	3	3	83	15	12
	(43)	(31)	(26)	(50)	(25)	(25)	(40)	(30)	(30)	(75)	(14)	(11)
Incline Creek	170	220	240	90	60	60	12	7	7	46	23	18
	(27)	(35)	(38)	(43)	(29)	(28)	(46)	(27)	(27)	(53)	(26)	(21)
Total	420	520	590	520	290	290	65	38	37	200	72	64
(rounded)	(27)	(34)	(39)	(47)	(27)	(26)	(46)	(27)	(27)	(60)	(21)	(19)

mary report by using improved maps available in 1975. Development areas were generally determined for individual stream drainages on the basis of natural drainage divides; however, urban drainage design modified the natural drainage boundaries between some major tributary basins. Some obvious alterations of natural drainage areas between First and Second Creeks were taken into account when the magnitudes of developed areas of those two basins were determined, but no similar adjustments were attempted between other drainages because cross-basin area changes were either less obvious or uncertain. Final estimates of developed and undeveloped drainage areas are believed to be of acceptable accuracy for generalizing sediment-yield estimates in this summary report. The revised estimates of developed and undeveloped areas used to calculate sediment yields in this report are shown in table 1.

Sediment-sampling intensity was greatest, and water discharge determinations were more accurate, at measurement sites near the mouths of the five principal creeks than at the upstream sites on the various tributaries. Consequently, annual sediment-transport estimates for sites nearest the lake are more reliable than those for the upstream, generally undeveloped areas.

As a result of the restraints on accurately determining sediment yields from developed versus undeveloped areas described above, and the inherent problems of proper comparison and interpretation of yield differences, the sediment-yield analysis method used in this report should be considered only a general guide to understanding differences in sediment movements from various drainages and areas of different land uses.

Sediment yields from the total drainage areas of the five principal study-area creeks are summarized in table 10. Second and Third Creeks consistently have the highest and next highest yields, respectively, for both annual and overall study-period durations. This is, at least in part, caused by the continuing effects of recent catastrophic flash floods in the two drainages, as was discussed in the report section Sediment Discharges, Loads, and Concentrations of Principal Drainages. The channels continue to readjust toward new equilibrium conditions. One product of these readjustments is greater-than-normal sediment discharges, particularly during relatively brief periods of high streamflow. Annual yields of First and Second Creeks increased sharply during 1971, compared to 1970, probably mainly because of subdivision construction during the summer of 1970.

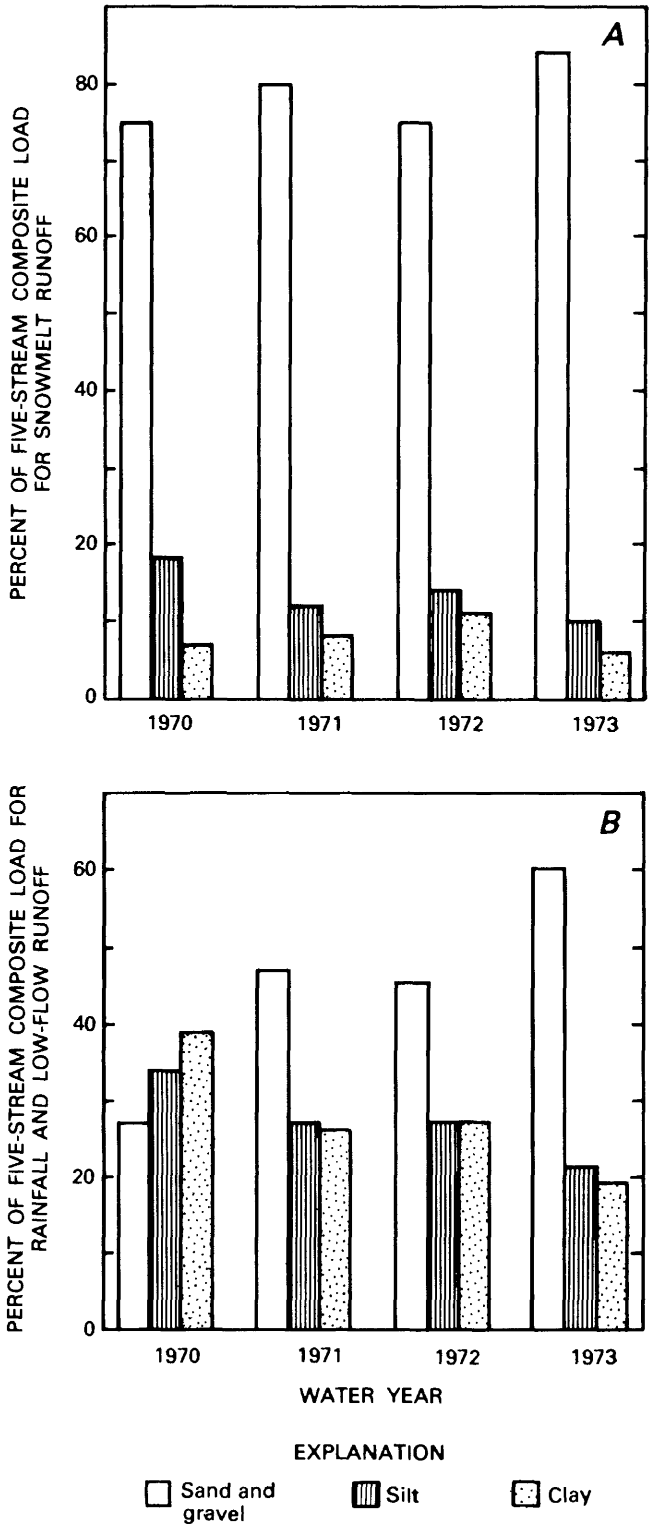


Figure 13. Estimated particle-size distribution of sediment loads from principal streams to Lake Tahoe during, *A*, snowmelt runoff and, *B*, rainfall and low-flow runoff.

Yields decreased from both Wood and Incline Creeks between 1970 and 1971; these decreases probably were the result of paving streets and gutters in the summer of 1970, thereby reducing sources of sediment exposed during early phases of road construction in 1969 and early 1970. The asphalt sealing of roadways and the completion of street storm drains before the onset of the 1971 water year (October 1970) restricted to some degree the severe erosion that prevailed throughout the prior runoff season. The sharp drop in yields of all drainages during 1972 was mainly the result of reduced runoff that year, which emphasized again the high sensitivity of sediment discharge to quantities and intensities of runoff. The sediment yield of Wood Creek increased in 1973 (table 10), but reasons for this increase are unknown to the author.

Table 10. Summary of estimated sediment yields to Lake Tahoe from principal drainages

[Sediment yields differ from those published earlier in progress reports (Glancy, 1971, 1973, and 1976a) because of drainage-area revisions. Sediment yields in tons per square mile]

Stream	Water year 1970	1971	1972	1973	Study-period average (rounded)
First Creek........	170	670	70	610	380
Second Creek......	890	1,900	310	1,100	1,000
Wood Creek.......	470	190	10	340	250
Third Creek.......	810	860	120	730	630
Incline Creek......	420	210	21	190	210
Five-stream composite (rounded).	560	620	84	490	440

Estimated annual sediment discharges and yields from the generally undeveloped and developed parts of principal study-area drainages are summarized in table 11. The relatively large loads and yields of Second and Third Creeks, particularly from undeveloped areas, are apparent in table 11, as they were in table 10, again the result of recent flash floods. Data of table 11 generally indicate that the annual fluctuations of sediment yields from both the undeveloped and developed areas are somewhat related to annual runoff fluctuations.

Developed-area yields are consistently much greater than those of undeveloped areas. As an annual five-stream composite, developed-area yields ranged from 10 to 12 times greater than undeveloped-area yields. Therefore, developed-area sediment yields are generally characterized as exceeding those of undeveloped areas by about 10 to 1 during the course of this study. This general characterization should be tempered by the above-mentioned deficiencies of the sediment-yield rating system. The characterization does not imply that development in the Incline Village area furnished 10 times more sediment to Lake Tahoe than did undeveloped areas, because areas of development and nondevelopment are unequal. Also, there is no known method of separating man-caused erosion from natural erosion within the developed areas; separation is possible only when adequate

Table 11. Summary of estimated sediment loads and yields to Lake Tahoe from undeveloped and developed areas of principal drainages

[Sediment yields are based on drainage areas listed in table 1. Yields differ from those published earlier in progress reports (Glancy, 1971, 1973, and 1976a) because of drainage area revisions. U, undeveloped; D, developed. Load in tons; yield in tons per square mile]

Basin	Part	Water year 1970 Load	1970 Yield	1971 Load	1971 Yield	1972 Load	1972 Yield	1973 Load	1973 Yield
First Creek	U	50	48	100	99	10	10	80	79
	D	150	1,500	680	4,200	73	460	630	3,900
Second Creek	U	1,000	710	1,100	930	90	76	500	420
	D	400	2,400	1,900	5,000	400	1,100	1,200	3,200
Wood Creek	U	120	82	100	68	5	3	70	48
	D	840	1,500	290	510	15	26	620	1,100
Third Creek	U	1,200	250	900	190	190	40	1,000	210
	D	3,700	3,100	4,300	3,300	550	430	3,400	2,600
Incline Creek	U	370	72	200	41	20	4	100	20
	D	2,500	1,400	1,300	620	130	62	1,200	580
Five-stream composite	U	2,700	190	2,400	180	300	23	1,800	140
(rounded)	D	7,600	1,900	8,500	1,900	1,200	270	7,000	1,600

data are available prior to the onset of development to allow comparisons of data collected during and after development.

Sediment Sources

The movement of sediment by flowing water depends on two major controlling factors: (1) an available supply of sediment and (2) flow of water adequate to move the sediment. There are numerous sources of sediment available for transport in the Incline Village study area, but the sediment generally does not become part of streamflow to Lake Tahoe until it is mobilized by naturally flowing water, by actions of mankind that alter natural runoff patterns, or by some combination of natural and man-related processes.

Most observations and data on sediment sources were collected in or very near the developed areas. Most undeveloped areas undergoing active erosion were inaccessible for study during critical times of intense erosion. Therefore, observations and data on sediment sources were unintentionally biased toward activities in the developed areas. This bias does not imply that natural sediment sources within undeveloped areas are less important, only that they are less accessible for measuring.

No attempts were made to quantify seasonal or annual sediment transport from specific point sources. However, instantaneous sediment-transport data were often collected in conjunction with qualitative observations of prolific sediment movement from specific point-source areas. These data were published in an earlier report (Glancy, 1976b).

The majority of instances of observed sediment movement could be field traced to some point source. However, during periods of high-altitude snowmelt when data above and below areas of development indicated a substantial pickup of sediment along main-stream channels in developed areas, precise locations of pickup were obscure. Because low-altitude runoff and minor-tributary sediment movement to the major stream channels from within developed areas were minimal during the high-altitude snowmelt period, sediment pickup in the developed area was concluded to be mainly the result of main-stem channel erosion. However, because no measurements were made of main-stem–channel morphological changes, whether this assumed channel erosion was largely the result of natural or of man-affected causes is unknown.

Man's modifications of major stream channels in developed areas include some stream-channel rerouting, extensive riparian vegetation changes, extensive channel riprapping, and the installation of numerous main-channel drainage structures. Therefore, much of the apparent main-stem channel erosion within developed areas, specifically during high-altitude snowmelt runoff, could have been a natural readjustment response to channel alterations by man.

The most dramatic sediment movements in the study area known to the author were those of the 1965 and 1967 flash floods on Third and Second Creeks, respectively. The Second Creek mudflow results were observed by the author about 15 hours after the flood. Although the mudflow occurred about 2 years prior to the onset of this study, its effects influenced current study results. The mudflow is discussed in detail in a previously published report (Glancy, 1969) and is, therefore, only briefly discussed in this report as it relates to this study. A characteristic that deserves particular emphasis is the predominantly natural genesis of the mudflow; this genesis contrasts with the apparently man-related sediment movement and sources that were dominant during this study. The sediment that constituted the mudflow was derived mainly from sheet and rill erosion high in the drainage basin and from the scour of alluvial channel fill throughout the length of Second Creek.

The character of the mudflow sediment differed somewhat from that measured during this study in that it contained considerably larger particle sizes. Figure 14*A* shows several transported boulders as large as 7 ft in diameter. Figures 14 and 15 show that organic (nutrient-related) debris of various sizes made up a conspicuous part of the mudflow material. Figure 14*B* depicts the use of manmade roadcuts rather than the normal stream channels as conduits for the mudflow and further details the character of the sediment. Deposition of some of the mudflow debris in Lake Tahoe is documented in figure 15.

Of particular interest to this study, figure 16 shows Second Creek channel banks still naturally caving and sloughing large amounts of debris about 2 years after the flood. This debris is moving into the path of streamflow that will easily carry much of the debris to the lake during normal storm and snowmelt runoff. This specific example of bank caving and many other examples observed along Second Creek's undeveloped channel reaches are related largely to natural readjustments of the stream system to the severe effects of main-channel erosion caused by the mudflow several years earlier. Examples of this type of prolonged natural feeding of sediment to stream channels as a result of earlier severe flooding are also prevalent along the undeveloped reaches of Third Creek. This process probably accounts in large part for the above-average sediment yields of the undeveloped areas of both Second and Third Creeks.

Other natural sources of sediment are common in the study area, but the sources contributing the largest amounts of sediment are probably related mainly to channel and undeveloped land-surface instability and therefore affect sediment transport in much the same manner as that described above.

Man-caused or man-accelerated sediment sources are of major importance in this report because the study data indicate that developed-area sediment yields are consistently much greater than those of undeveloped areas. The most noticeable man-related sediment sources, both in apparent magnitude of sediment yields and frequency of occurrence, are those associated with roads. The apparent dominance of association between sediment yields and roadways may be partly because large areas of new subdivision developments had not progressed much beyond the road- and street-construction stage during the period of investigation. Regardless, most of the obvious sediment sources were associated with both very new and older roadways and street drainage.

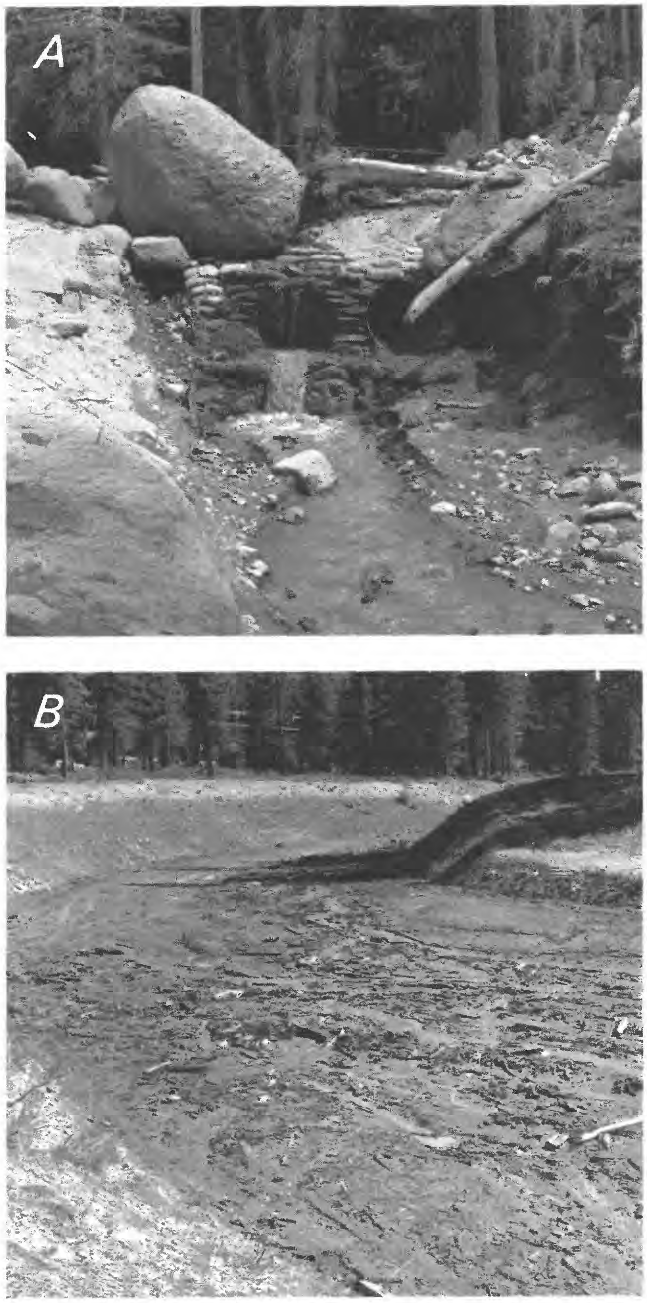


Figure 14. Results of the Second Creek mudflow of August 25, 1967. *A*, Transported boulders and trees. *B*, Mixed organic and inorganic debris diverted by a highway roadcut. Photographed on August 26, 1967.

A particularly severe example of erosion caused by road construction is located in the Second Creek drainage basin above the main subdivision development. An unpaved utility roadway was constructed in decomposed granite terrain and is an example of mass-wasting erosion problems that can occur when this type of steeply sloping landscape is disturbed by roadcuts. The time-lapse photographic sequence of figure 17 documents landscape

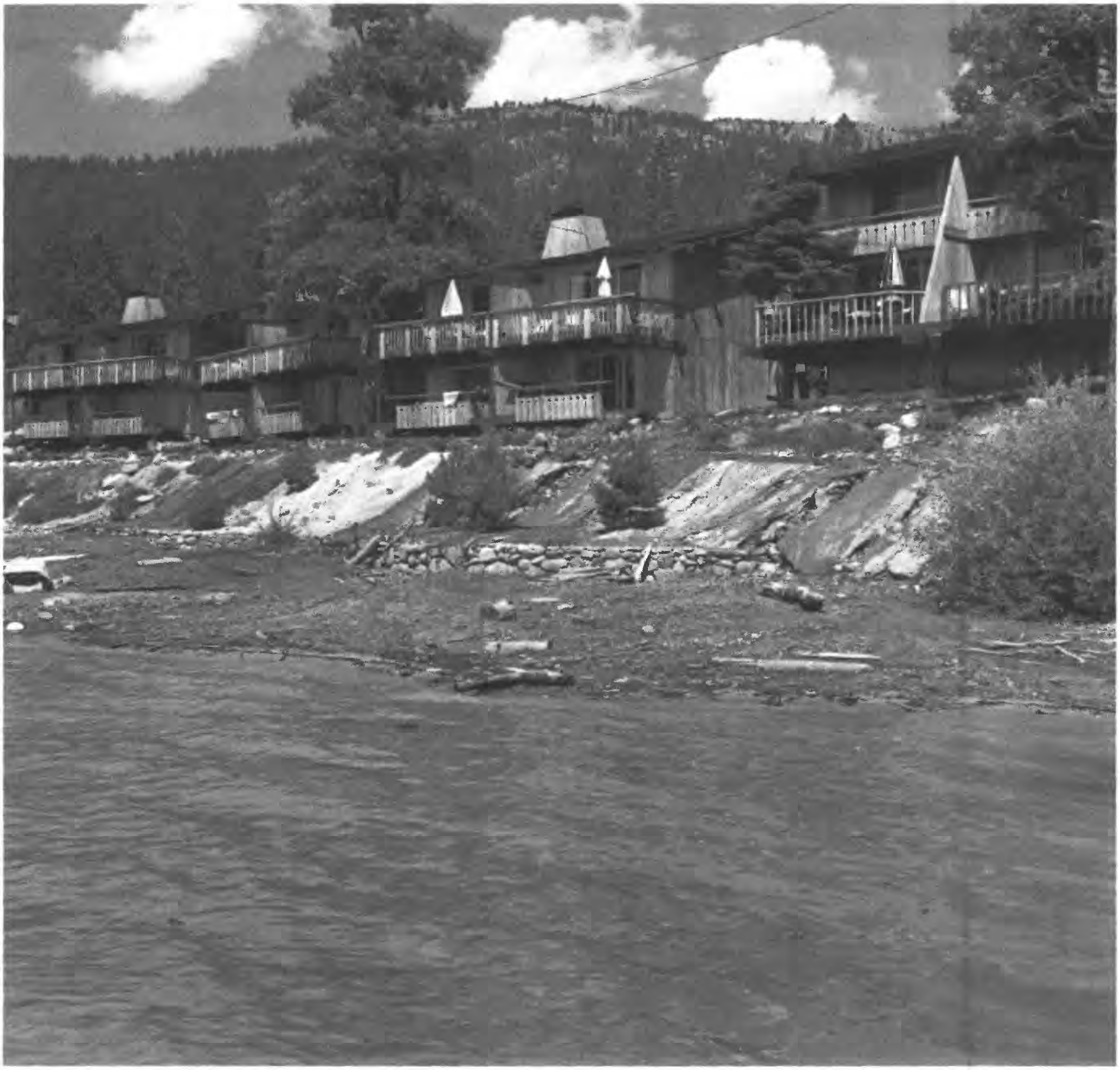


Figure 15. Organic and inorganic debris dumped into Lake Tahoe during Second Creek mudflow of August 1967. Photographed on August 26, 1967.

changes at a site along this utility road over a several-year period.

Figure 17*A*, photographed near the end of the 1970 spring-snowmelt runoff, shows heavy sloughing and caving of the near-vertical roadcut that transects the steeply sloping manzanita-vegetated mountainside. Snowmelt runoff down the steeply sloping roadway severely eroded the unprotected road surface and concentrated much of its flow against the toe of the vertical cut, as shown in figure 17*A*. The concentrated runoff was thus able to pick up large additional quantities of sediment from the actively sloughing cut slope and subsequently to move it farther downslope toward Second Creek where much of the material thus transported combined with Second Creek flow.

The site was further transformed during the following year, as shown in figure 17*B*. Erosion during 1971 spring-snowmelt runoff moved out additional large quantities of sediment furnished by the sloughing cut slope, in addition to removing sediment from debris apparently

Figure 16. Landsliding to Second Creek as photographed on September 8, 1969, caused mainly by severe channel disturbance resulting from the 1967 mudflow.

dumped on the site by man from elsewhere. Again, Second Creek incorporated much of this locally derived sediment into its lakeward flow.

The processes of mass wasting and erosion continued through the next year, as shown in figure 17*C*, even though attempts were apparently underway to stabilize the cut slope with boulders and uprooted tree stumps. A manmade benchlike terrace had been constructed along the hillslope side of the road by 1973 (fig. 17*D*), but continued mass slumping of the cut slope is evident. The slope continued to unravel during the following 2 years, as figure 17*E* shows, although some revegetation of the terrace occurred. Instability of the unpaved roadway and of the fill material on the downslope road shoulder during the spring of 1970 is shown in figure 18, as some of the roadbed moved downslope toward Second Creek.

Figures 17 and 18 dramatize some serious immediate and long-term erosion problems associated with road construction in steeply sloping, fragile landscapes. The site shown in figures 17 and 18 represents one of the most intense and persistent eroding sites observed in the area during the study. Although some of the sediment derived from this site was dispersed over the landscape along the route to Second Creek, much of the sediment traveled almost immediately to the creek. The characteristics of erosion at this site dramatically emphasize the point-source nature of much of the erosion in the study area. Quantitative data collected from runoff at this site are listed in one of the previously published study reports (Glancy, 1976b, table 1, p. 6, sites 9 and 10).

Examples of dramatic, but equally persistent, roadcut erosion are commonplace throughout the developed areas. Uncompleted subdivision roads that remain unpaved during winter months can yield abundant sediment to lake tributary streams. Figure 19 depicts the effects of spring-snowmelt erosion of an unpaved street in Incline Village subdivision unit 2 (table 2, fig. 4) during April 1970.

A somewhat typical example of sediment transport from older completed roadways is shown in figure 20. At this site, a steeply sloping cut in poorly consolidated sediment deposits continually supplies significantly large quantities of dominantly sand-sized and finer grained material to an unlined gutter. The gutter is fed by a fairly large urban drainage area and frequently transmits flows of rainfall and snowmelt runoff at velocities sufficient to transport fine-sized gravel. This particular gutter drains to First Creek about 100 ft downgradient from the photograph site, and the small flow of sediment-laden water in the gutter is near the junction of the gutter and First Creek. In figure 21*A*, snowmelt runoff is being diverted over the roadway by the same gutter, clogged with snow. Figure 21*A*, in conjunction with the view presented in figure 21*B*, provides some perspective on the amount and character of the sediment transported by this drainage system. This roadside drainage continues to yield noticeable quantities of sediment to First Creek even though the roadway was constructed over a decade before the scenes in figures 20 and 21 were photographed (tract 4, table 2, fig. 4). This site displays sediment-source characteristics typical of many gutters in the older subdivision developments of the area.

Fresh roadcuts left unprotected during the heavy runoff season also were vulnerable to extensive erosion, particularly during periods of heavy rainfall, as shown in figure 22. Advanced stages of rilling caused by repeated intense runoffs cause a deeply scarred landscape like that of figure 23 at Incline High School, located just east of subdivision tract 8 (table 2, fig. 4).

Underroad drainage pipes that spill their contents as high-energy flow onto unprotected land surfaces can cause severe erosion. Figure 24 shows an example of this problem in development tract 31 (table 2, fig. 4). The culvert flow erodes not only the toe of the roadway fill, but, at times of high flows, the flow also has the potential to erode the flood plain of West Branch Incline Creek on which it spills.

Timber clearing and land-surface grading, particularly if done with little attention to maintaining the integrity of natural runoff channels or to the timing of the construction activity, often supply large amounts of sediment to streamflow. An example of this type of problem is shown in figure 25. In this figure, the perennially flowing

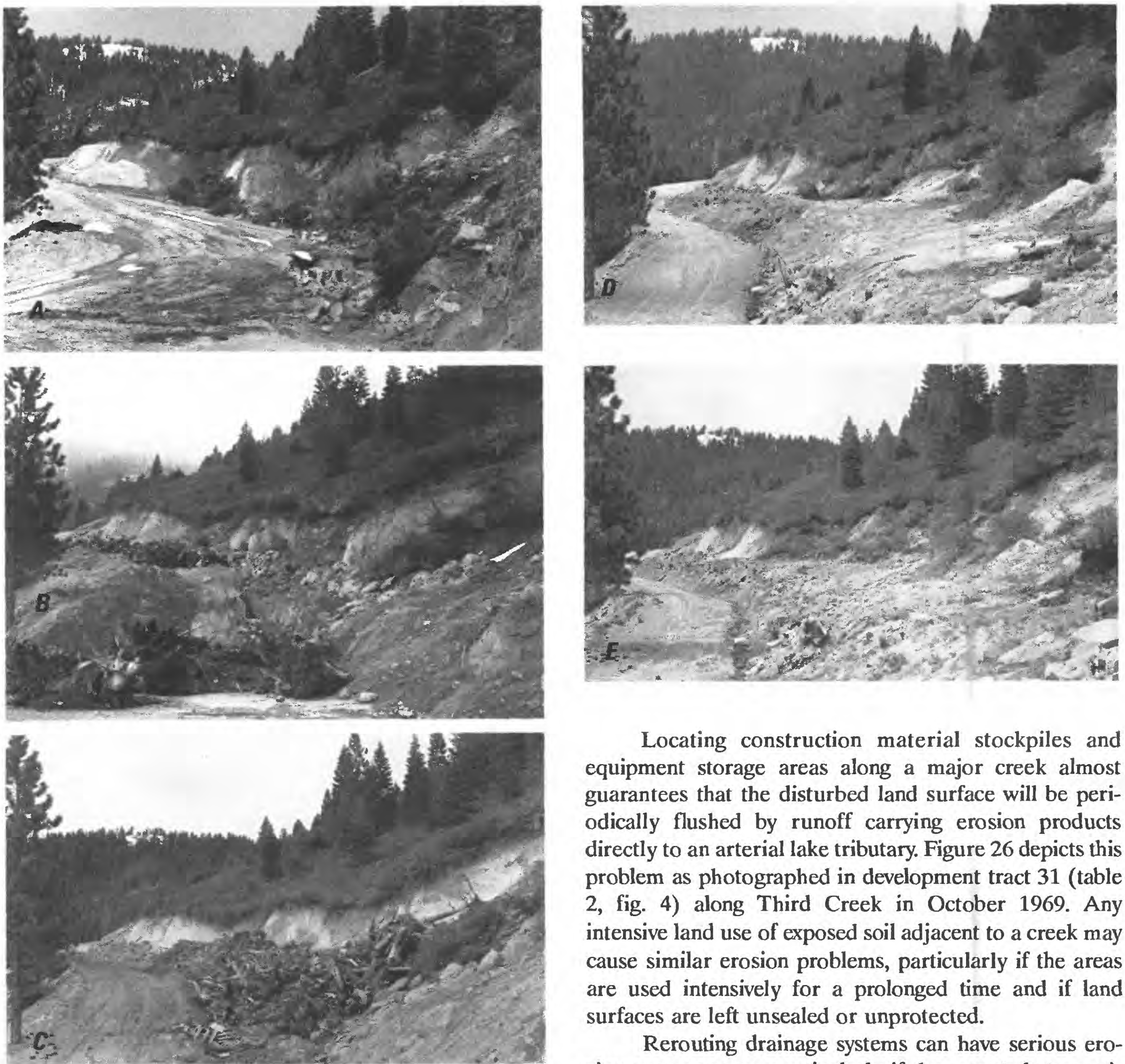


Figure 17. Erosion and mass wasting of a roadcut in the Second Creek drainage. *A*, April 2, 1970; *B*, May 4, 1971; *C*, March 20, 1972; *D*, May 12, 1973; and *E*, June 2, 1975.

West Branch Third Creek is in direct contact with freshly disturbed and easily erodible topsoil. The photograph was taken on October 19, 1969, near the beginning of the annual storm and runoff season. New construction begun late during the fair-weather season will almost certainly expose disturbed land surfaces to intense runoff of the annual storm and snowmelt seasons before the construction is completed.

Locating construction material stockpiles and equipment storage areas along a major creek almost guarantees that the disturbed land surface will be periodically flushed by runoff carrying erosion products directly to an arterial lake tributary. Figure 26 depicts this problem as photographed in development tract 31 (table 2, fig. 4) along Third Creek in October 1969. Any intensive land use of exposed soil adjacent to a creek may cause similar erosion problems, particularly if the areas are used intensively for a prolonged time and if land surfaces are left unsealed or unprotected.

Rerouting drainage systems can have serious erosion consequences, particularly if the rerouted stream is allowed to carve its own channel and must then hydraulically self-equilibrate over a prolonged time. Figure 27 shows the erosional status of such a rerouted stream during an intermediate stage in the reequilibration process. Severe channel erosion takes place over an extended time period before the channel reaches a hydraulic equilibrium state in which variable flow conditions cause minimal erosion.

Some artificial stream-channel protection may help reduce erosion in cases where major channel modifications are performed during development. Figure 28 shows a riprapped reach of Third Creek. Riprapping is one method of reducing large-scale channel cutting. However, protective measures such as riprapping may

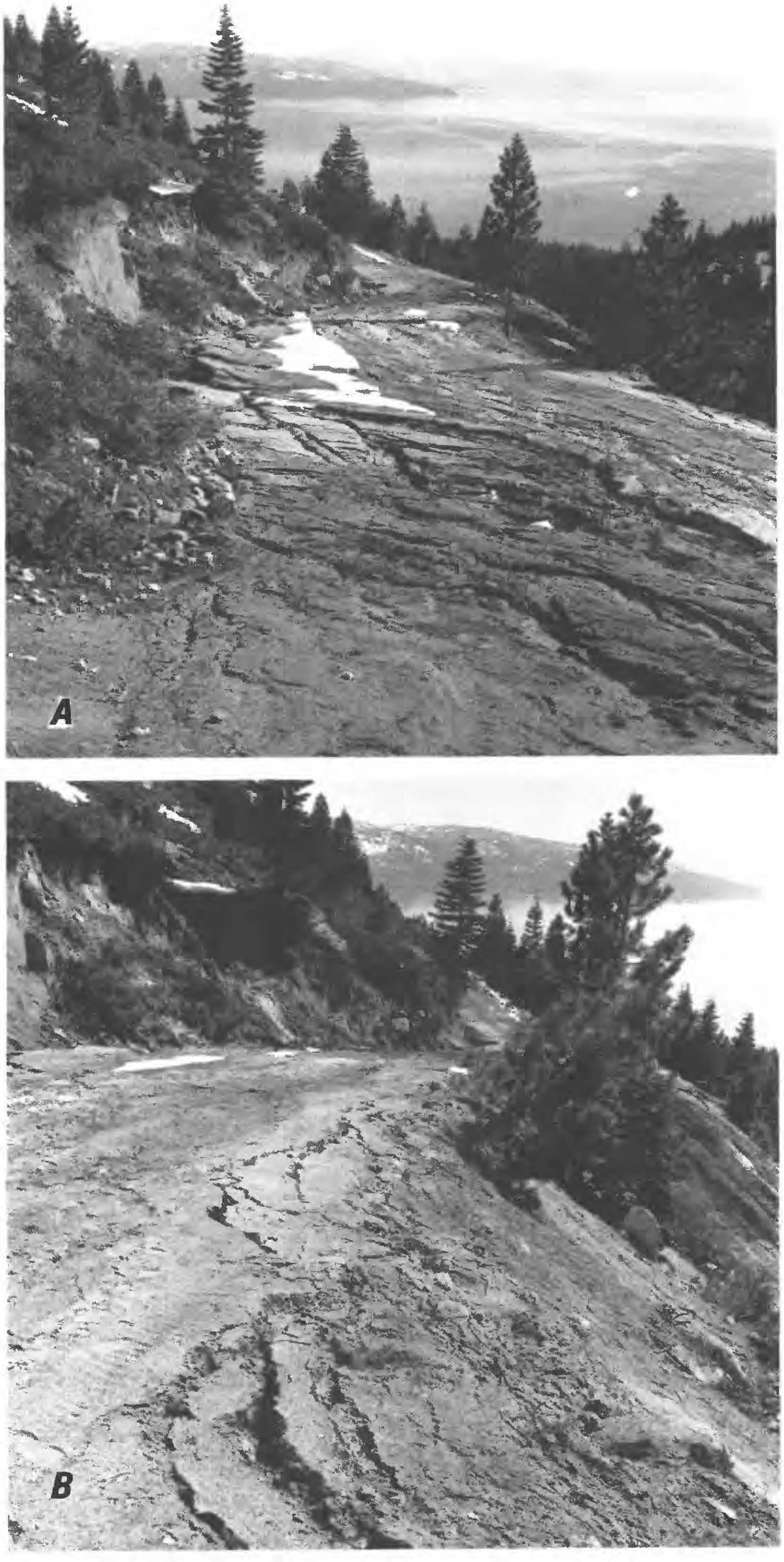


Figure 18. Examples of roadway erosion in the Second Creek drainage. *A*, intense road-surface rilling and gutter erosion. *B*, Slumping and potential sliding of the roadway shoulder fill. Photographed on April 2, 1970.

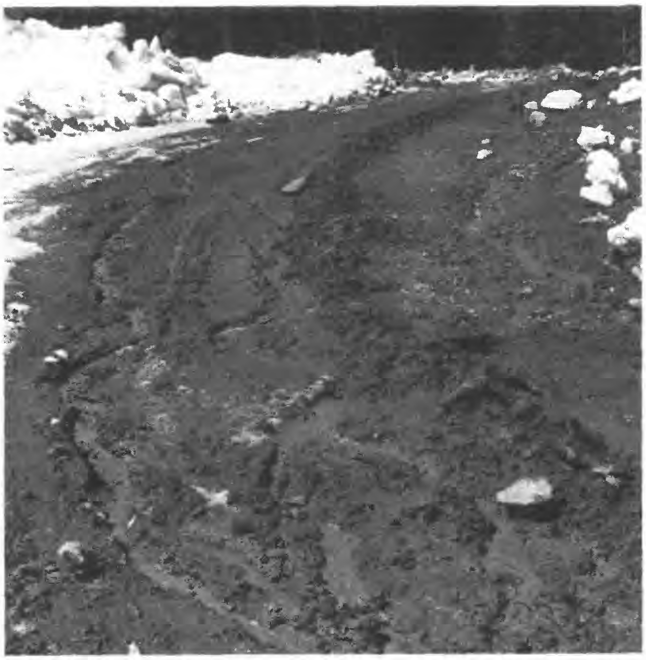


Figure 19. Snowmelt-runoff erosion of a partly constructed street in Incline Village development unit 2 on April 4, 1970.

Figure 20. Unlined road gutter having a continual supply of sediment from a steep roadcut. Photographed on April 22, 1973.

introduce other serious environmental problems, even though they provide effective local erosion control.

The above-cited and illustrated examples of sediment sources, both natural and man caused, are not intended as a comprehensive documentation of all types of sources in the study area. Instead, the examples are intended as an overall guide to the general types of sediment sources that were readily observed. The photographs are intended to portray striking visual examples; therefore, readers should realize that numerous, more subtle sediment sources are commonplace throughout the area.

Sediment Discharges of Minor Drainage Basins

The scope of this investigation did not permit adequate data collection to assess sediment discharges of minor drainages as thoroughly as was done for the principal creeks. However, data were frequently collected from several minor drainages, including Mill Creek, an unnamed tributary to the lake just west of First Creek, and two unnamed lake tributaries between Second and Wood Creeks. These data are included in a U.S. Geological Survey open-file report of miscellaneous hydrologic data collected during this investigation (Glancy, 1976b, table 1).

The unnamed lake tributary west of First Creek is probably the only minor drainage course that would properly qualify as a perennially flowing stream; during the study period, it flowed at least 90 percent of the time. However, it may not flow for prolonged periods during below-average runoff years, particularly during periods of severe drought. Enough data were collected near the mouth of this creek to allow rough estimates of its annual sediment discharge to Lake Tahoe. These estimates are 1970, 60 tons; 1971, 40 tons; 1972, 15 tons; and 1973, 25 tons. Of the 0.67-mi^2 drainage area of this creek, 0.07 mi^2 near its mouth is in the developed area, and about 0.6 mi^2 is generally undeveloped. Data analyses suggested that this creek's developed-area yields during this study ranged from about 100 to 500 t/mi^2 and that undeveloped-area yields ranged from about 10 to 50 t/mi^2. Measured sediment concentrations of the creek at the sampling site ranged from 1 to 10,200 mg/L. Measured instantaneous sediment discharges ranged from 0.00003 to 8 t/d. Data were insufficient to characterize the particle-size distribution of the annual sediment discharge.

The combined drainage area of the two unnamed lake tributaries between Second and Wood Creeks is about 1 mi^2 and lies mostly within the zone of development. Both tributaries are ephemeral drainages and probably flow less than one-fourth of the time during most years; both were sampled near their mouths. Samples collected from the westernmost tributary were as high as 56,400 mg/L in sediment concentration, and instantaneous sediment discharges were as great as 150 t/d (Glancy, 1976b, table 1, site 14). Measured sediment concentrations of the easternmost tributary reached

Figure 21. Road gutter depicted in figure 20, during snowmelt runoff, showing, *A*, the turbid character of snowmelt runoff caused mainly by the fine-grained (silt and clay) component of moving sediment and, *B*, road-surface deposits of the coarse-grained (sand and gravel) component of the load. Photographed on April 14, 1972.

Figure 22. Deep, steeply sloping roadcut near the Incline ski area on December 19, 1969, showing, *A*, rainfall-runoff erosion of the unprotected exposure and, *B*, vertical undercutting of the slope by rill and sheet flow collecting into a resultant gutter.

10,200 mg/L, and instantaneous sediment discharges were as much as 20 t/d (Glancy, 1976b, table 1, site 15). Although both tributaries had large ranges of sediment concentrations, and at some times during the study were transporting sediment loads greater than some of the five principal creeks, their generally short flow durations and relatively low water discharges strongly suggest that their average annual sediment discharge to the lake is small compared to that of the principal drainages. Annual estimates of sediment delivery by these two tributaries to the lake were not feasible.

Mill Creek, another ephemeral stream, having about a 2-mi^2 drainage area, was sampled from time to time. The sampling complexities and the ephemeral

Figure 23. Advanced stages of rill erosion of bare-ground slopes at Incline High School on November 9, 1969.

Figure 24. Elevated road-culvert exit that spills high-energy runoff on unprotected land surfaces. Photographed on November 12, 1969.

nature of Mill Creek flow relegated that drainage to a minor status for purposes of this investigation. Observations of Mill Creek suggested that the creek flowed less than half the time during the study period. Measured sediment concentrations of the main stem and of its major downstream tributary fluctuated widely (up to 60,000 mg/L), as did instantaneous sediment discharges (up to 160 t/d). Estimated water discharges never exceeded 2 ft^3/s in either of the channels during sampling of intensive runoff; therefore, the total streamflow of Mill Creek to Lake Tahoe is assumed minor compared to that of any of the five principal creeks. Over one-third of the Mill Creek drainage lies within the general development area, and the wide fluctuations of sediment concentrations and discharges suggest that, during short periods of intensive runoff, Mill Creek can deliver sizable sediment loads to the lake. However, data collected during the study were not sufficient to assess the creek's annual sediment discharge to Lake Tahoe.

These four tributaries to the lake may collectively deliver annual sediment loads to Lake Tahoe similar in magnitude to that of either Wood or First Creeks. Thus, the tributaries collectively should be considered significant sediment contributors in the study area. Their composite drainage area in the development zone (about 1.6 mi^2 or about 25 percent of the development) is large enough to merit greater investigative attention if more detailed studies are contemplated.

The numerous other tiny tributaries to the lake in the study area are all ephemeral drainages of very small size and infrequent flow; therefore, they are considered of minor importance in assessing either runoff or sediment transport to Lake Tahoe.

Figure 25. A tributary of West Branch Third Creek eroding a freshly cleared subdivision construction area on October 19, 1969.

Figure 26. Construction materials and equipment storage along the erodible banks of Third Creek during October 1969.

Study Results Compared with Other Known Study-Area Data

The sediment-transport data summarized in this report and those of the progress reports are put in better perspective if they are considered in relation to other currently available sedimentation data for the Incline Village area. The only known data are those for the 1967 mudflow in the Second Creek drainage (Glancy, 1969), discussed in the section Sediment Sources. The mudflow yielded an estimated 50,000 yd^3 of debris (35,000 yd^3 of dry sediment), having a sediment weight of about 75,000 t. The material moved as a result of a high-intensity rainfall on the upper drainage slopes and traveled from the undeveloped area into the developed area in probably less than 1 hour. The contributing area was probably only 0.5 mi^2. The resultant sediment yield was about 150,000 $(t/mi^2)/hr$. If the yield were prorated over the entire 1.8-mi^2 Second Creek drainage (the most conservative statistical technique), the resultant yield would be about

Figure 27. A rerouted segment of West Branch Third Creek near its junction with Third Creek, depicting severe erosion problems as the channel adjusts to new equilibrium hydraulic conditions. Photographed on April 11, 1970.

Figure 28. Riprapped reach of Third Creek just downstream of Mount Rose Highway on October 30, 1969.

40,000 (t/mi^2)/hr. The total load (75,000 t) moved during that short time amounted to almost 2½ times the estimated cumulative 4-year total loads (31,000 t) of the five major streams in the Incline Village area. Other characteristics of the mudflow pertinent to this study were described in the Sediment Sources section. The residual effects of that flood event are still influencing erosion in the Second Creek drainage. Therefore, nature must be considered as a currently noteworthy, although sometimes unpredictable, participant on the Lake Tahoe basin erosion scene.

Some Thoughts and Suggestions on Erosion Control

The field-investigative part of this study involved numerous days of data collection throughout the area during all types of weather and runoff conditions. In addition to measuring runoff and sediment-transport characteristics, these intensive and prolonged field activities provided many opportunities to observe erosion and runoff characteristics of the terrain. The field observations and supporting data lead to the following conclusions regarding runoff and erosion.

Natural erosion is common in the Incline Village area. Natural erosion varies greatly from drainage to drainage and from place to place within individual drainage basins. Dramatic natural runoff events, such as the flash floods of Third and Second Creeks in 1965 and 1967, respectively, suddenly alter severely the natural runoff and erosion characteristics, and their effects linger for many years thereafter. They disrupt the equilibria of natural drainageways and extensively modify land-surface characteristics, generally accelerating sediment transport to the lake. Any attempts by man to reduce sediment transport caused by these natural events should be based on sound knowledge of the cause-and-effect relations. This knowledge will help formulate and initiate proper corrective actions.

That developed-area yields were generally about 10 times greater than those of undeveloped areas strongly implies that development has greatly accelerated erosion and sediment transport to Lake Tahoe from the Incline Village area. How long, and at what magnitude, this accelerated transport will persist cannot be determined without further documentation of time-related changes. Likewise, possible future erosion-control effectiveness cannot be properly evaluated without adequate data that document changes in sediment transport resulting from the control procedures.

Man's development activities accelerate erosion mainly by increasing the availability of sediment for fluvial transport and by concentrating surface runoff to a degree that allows mobilization of the available sediment. Concentrated runoff increases competence of the flowing water to move sediment that would otherwise be stable under dispersed-runoff conditions. Therefore, any prevention or reduction of erosion and sediment transport must reduce the availability of sediment and (or) disperse runoff.

Sediment availability can be reduced in several ways: (1) minimize land-surface disturbance; (2) confine necessary land-surface disturbance to areas that will not excessively expose easily erodible materials; (3) schedule land-surface disturbance only during late spring, summer, and early autumn to avoid increasing the sediment availability during periods of normally intensive runoff; (4) restabilize disturbed surfaces prior to seasonally recurring runoff periods; and (5) refrain from introducing foreign materials into the area that either qualify as available sediment or that may evolve into that classification during the foreseeable future. Most of the above stated objectives are technically feasible but in many cases may be expensive.

If erosion problems caused by development cannot be corrected immediately, natural processes can be allowed to reduce erosivity. A commonly observed example of man's thwarting natural land surface stabilization is the periodic regrading of unlined road gutters. This annual, or more frequent, regrading upsets the process that evolves naturally when gutter flow removes fine-grained sediment and concentrates coarse-grained particles at the surface that provide an armor coat against further erosion. The regrading thus perpetuates an unnatural state of accelerated erosion by reexposing fine-grained sediment to future contact with gutter runoff.

Storm-runoff collection and transmission systems are integral components of most real estate developments. Unfortunately, the collection of storm runoff generally tends to further concentrate flow; the concentration generally increases the competence of the runoff to move any unconsolidated sediment that it contacts enroute. Therefore, one way of reducing erosion and sediment transport is to disperse runoff rather than collect it. From a practical standpoint, however, some degree of storm runoff collection is often mandatory to prevent sheet flooding and ponding of runoff water in developed areas or to modify natural drainage networks that are incompatible with the development plan. If runoff must be collected, its sediment transport efficiency can be reduced by shielding the runoff from sediment available for transport and (or) by dispersing the runoff again as quickly as possible. Storm-drain system designers can also consider available alternatives to improve land-surface infiltration characteristics, if practicable, and thereby reduce the need to collect and transport runoff. The effectiveness of inhibiting sediment transport to Lake Tahoe by dispersing highway gutter runoff is demonstrated in the example of roadside drainage design in the Glenbrook Creek drainage along the east side of the lake (Glancy, 1977, p. 22).

Obviously, many techniques are available to inhibit erosion in development areas, both during and after construction activity. Great opportunity remains for innovative thinking and development of new and improved techniques. Many of the techniques will increase construction costs and complexities. Therefore, planners attempting to reduce erosion should first objectively consider thoroughly the environmental effects of different levels of erosion activity. Unfortunately, much of the knowledge necessary to assess the short- and long-range effects of sediment transport to Lake Tahoe is currently incomplete. Therefore, the optimum level of care required to maximize benefits and minimize detriments at a given level of financial investment is somewhat indeterminate at this time.

NUTRIENT TRANSPORT

The inflow of nutrients (primarily nitrogen and phosphorus) to Lake Tahoe has caused great concern during recent years that eutrophication of the lake will be accelerated through continued and increased nutrient inflow as a result of man's development activities in the Tahoe basin. The current conditions of eutrophication of Lake Tahoe were summarized by Goldman (1974, p. 1–2). Goldman's conclusions strongly implicate sediment input to the lake as a major catalyst to increased biological productivity and eutrophic activity.

Although this study is primarily concerned with water and sediment transport of five creeks tributary to Lake Tahoe, the study also includes a reconnaissance to assess nutrient movement to the lake by the two largest streams, Third and Incline Creeks. Nutrient data were collected concurrently with streamflow and sediment-transport data to investigate the interrelations of water, sediment, and nutrient movement in these two creeks near their mouths.

Nutrient Concentrations and Discharges

Nutrient data collected during this investigation are listed in table 12. The data are shown as nutrient discharges (transport rates); the nutrient-concentration data used as the bases for the discharges were previously published in progress reports for this study (Glancy 1971, 1973, and 1976a). Most nutrient data purposely were collected during times of intensive sediment movement to assess the magnitudes of nutrient concentrations and discharges during periods of intense erosion. A few additional nutrient samples were collected during low-flow periods when sediment transport was minimal. Thus, although the scope of the investigation allowed the collection of only a limited number of nutrient samples, the data were gathered during wide ranges of streamflows (2.0 to 81 ft^3/s) and of sediment-transport conditions (0.01 to 829 t/d). For comparison, streamflow at the sampling sites of

Table 12. Summary of nutrient and concurrent streamflow and sediment data for Third and Incline Creeks near their mouths

[Nutrient content in pounds per day]

Third Creek[1]

Date	Time	Discharge (ft³/s)	Water temperature (°C)	Dissolved nitrate as N[2]	Dissolved nitrite as N	Total ammonium as N	Dissolved ammonium as N	Total organic nitrogen as N	Particulate organic nitrogen as N[3]	Dissolved organic nitrogen as N	Total nitrogen as N[4]	Dissolved nitrogen as N	Total phosphorus as P	Particulate phosphorus as P[3]	Dissolved phosphorus as P	Dissolved orthophosphate as P	Dissolved silica as SiO_2	Total organic carbon as C	Specific conductance (µmho)	Total sediment concentration (mg/L)	Total sediment discharge (t/d)	Gravel	Sand	Silt[5]	Clay	Runoff character[8]
																						Approximate particle-size distribution of sediment discharge, in percent				
1969																										
Oct. 15	1500	5.0	5.0	—	—	—	—	—	—	—	—	—	2	—	—	—	—	—	74	70	0.94	0	2	27	71	R
Dec. 19	1730	9.0	3.5	12	0	1	—	170	—	—	180	—	24	—	—	12	—	—	70	1,270	31	0	[7]50	[7]40	[7]10	R
1971																										
Mar. 19	1740	6.5	5.0	4	0	25	—	15	—	—	42	—	9	—	—	1	600	—	74	404	7.1	0	68	16	16	LAS
Mar. 23	1100	6.8	2.0	2	0	40	—	14	—	—	55	—	6	—	—	4	660	—	83	191	3.5	0	79	[5]21		LARS
Mar. 25	1500	9.8	3.5	11	1	31	—	16	—	—	58	—	34	—	—	11	790	—	75	1,400	37	7	39	30	24	LARS
May 7	1315	11	9.0	2	0	5	—	39	—	—	46	—	18	—	—	6	—	—	69	600	18	0	76	14	10	LARS
May 14	1810	19	9.5	7	0	12	8	37	15	22	56	37	41	—	—	5	—	—	47	1,600	86	0	78	16	6	MHAS
June 12	1830	57	8.0	10	0	34	20	65	—	—	110	—	110	—	—	6	—	—	30	2,040	314	19	75	5	1	HAS
June 20	1840	81	11.5	30	0	4	—	160	70	87	190	—	150	—	—	13	—	—	33	3,790	829	7	58	4	0	HAS
1972																										
Mar. 3	1745	10	5.0	12	0	12	9	42	30	12	65	33	25	—	—	4	860	350	65	302	8.2	0	25	43	32	LAS
Apr. 5	1120	7.9	3.5	2	0	6	6	26	24	2	34	9	8	—	—	0	730	470	65	322	6.9	0	38	31	31	LAR
May 29	1930	36	10.5	6	0	25	10	56	52	4	87	19	52	—	—	2	2,500	970	27	1,170	114	19	66	10	5	HAS
Nov. 4	0040	11	4.0	5	1	12	10	71	47	24	89	41	20	14	6	4	710	1,000	60	752	22	7	59	17	17	R
1973																										
Mar. 25	1550	8.2	6.5	5	0	4	4	31	19	12	39	20	16	15	1	2	710	530	95	265	5.9	0	41	35	24	LAS
Apr. 4	1615	9.0	6.5	[2]53		3	4	—	—	20	—	30	—	—	3	—	—	—	83	313	7.6	0	65	20	15	LAS
Apr. 22	1700	11	9.5	2	.6	5	2	17	16	1	26	6	8	6	2	1	1,000	—	73	444	13	0	87	9	4	MAS
May 1	1745	16	8.5	3	0	0	0	—	—	23	—	28	4	2	3	.9	1,400	350	54	150	6.5	0	87	[5]13		MAS
May 18	1800	65	6.0	20	0	10	7	110	81	20	140	53	42	39	4	4	3,900	1,800	27	3,000	527	21	75	3	1	HAS
May 28	1915	68	9.0	10	0	10	10	170	120	30	190	51	62	59	4	4	4,800	2,200	28	1,970	362	30	66	3	1	HAS
May 29	1130	36	11.0	4	0	4	2	33	20	20	41	23	10	8	2	2	2,900	490	31	404	39	0	97	[5]3		HAS
May 31	1530	76	8.5	4	0	30	30	410	310	100	450	140	190	190	4	4	4,900	6,600	30	3,200	656	31	60	7	2	HAS, LAR
June 22	1900	7.4	11.5	.4	0	0	.4	4	.8	4	5	4	2	.8	.4	.6	720	60	49	5	.10	—	—	—	—	SLF
Sept. 14	1215	2.0	13.5	0	.1	.1	.1	.6	.2	.4	.9	.6	.4	0	.4	.6	190	11	71	2	.01	—	—	—	—	SLF

Table 12. Summary of nutrient and concurrent streamflow and sediment data for Third and Incline Creeks near their mouths—Continued

Incline Creek[1]

Date	Time	Discharge (ft^3/s)	Water temperature (°C)	Dissolved nitrate as N [2]	Dissolved nitrite as N	Total ammonium as N	Dissolved ammonium as N	Total organic nitrogen as N	Particulate organic nitrogen as N [3]	Dissolved organic nitrogen as N	Total nitrogen as N [4]	Dissolved nitrogen as N	Total phosphorus as P	Particulate phosphorus as P [3]	Dissolved phosphorus as P	Dissolved orthophosphate as P	Dissolved silica as SiO_2	Total organic carbon as C	Specific conductance (μmho)	Total sediment concentration (mg/L)	Total sediment discharge (t/d)	Gravel	Sand	Silt[5]	Clay	Runoff character[6]
																						Approximate particle-size distribution of sediment discharge, in percent				
<u>1969</u>																										
Dec. 19	1715	14	3.0	8	0	13	—	190	—	—	210	—	61	—	—	14	—	—	65	1,620	61	0	[7]40	[7]40	[7]20	R
<u>1970</u>																										
Nov. 24	2300	12	5.5	2	1	14	—	47	—	—	64	—	32	—	—	19	—	—	61	1,860	60	0	38	25	37	R
<u>1971</u>																										
Mar. 19	1715	8.4	5.0	5	.5	38	—	17	—	—	64	—	14	—	—	7	950	—	84	806	18	9	39	28	24	LAS
Mar. 23	1040	9.8	2.0	8	.5	64	—	21	—	—	95	—	13	—	—	8	1,100	—	99	424	18	5	41	28	26	LARS
Mar. 25	1445	14	3.5	6	3	72	—	29	—	—	110	—	30	—	—	26	1,400	—	81	1,300	49	5	26	33	36	LARS
May 7	1245	19	8.0	8	0	9	—	67	—	—	84	—	—	—	—	7	—	—	64	812	42	0	44	30	26	LARS
May 14	1830	31	9.0	15	0	10	13	100	69	32	130	60	87	—	—	7	—	—	45	1,440	121	6	74	14	6	MHAS
<u>1972</u>																										
Mar. 2	1715	11	4.5	9	0	24	8	31	19	12	65	29	18	—	—	2	1,400	420	76	247	7.3	0	9	38	53	LAS
Apr. 5	1100	8.0	3.5	4	0	3	3	12	7	5	19	11	6	—	—	.4	860	430	62	208	4.5	0	11	48	41	LAR
Nov. 4	0015	12	4.5	0	3	25	.6	100	91	13	130	17	54	51	3	3	840	1,700	57	962	31	11	23	26	40	R
<u>1973</u>																										
Mar. 25	1615	9.8	5.0	6	0	6	4	43	22	21	53	31	16	14	2	3	1,000	1,100	101	344	9.1	0	50	30	20	LAS
Apr. 4	1600	9.4	7.0	[2]5		6	3	—	—	22	—	30	—	—	2	—	—	—	82	384	9.7	0	58	24	18	LAS
Apr. 22	1630	16	8.0	9	0	5	2	36	25	11	50	22	16	14	2	2	1,700	—	64	1,140	49	7	82	8	3	MAS
May 1	1820	22	7.0	12	0	6	4	38	23	15	56	31	13	10	4	1	2,300	780	55	544	32	11	81	6	2	MAS
May 18	1730	28	8.5	10	0	12	5	53	44	9	76	24	10	8	3	2	2,600	910	42	149	11	0	82	[5]18		HAS
May 28	1900	18	11.5	2	0	1	1	19	3	17	25	22	4	3	1	1	1,700	290	43	180	8.7	0	94	[5]6		HAS
May 31	1500	36	9.5	4	0	10	—	310	250	58	330	68	100	97	6	4	3,100	3,500	57	665	65	0	57	26	17	RHAS
June 22	1845	9.4	11.0	0.5	0	1	0	6	0	6	8	7	3	2	.5	.5	1,100	100	54	10	.25	—	—	—	—	SLF
Sept. 14	1200	3.7	13.0	3	0	2	.2	1	1	0	6	3	1	0	1	1	480	40	67	5	.05	—	—	—	—	SLF

[1]Nutrient concentrations for these samples were published in progress reports (Glancy, 1971, p. 16; 1973, p. 24; and 1976a, p. 28).

[2]Combined nitrate and nitrite quantities.

[3]Determined as the difference between total and dissolved components.

[4]Assumes that total nitrate and nitrite equal dissolved nitrate and nitrite, respectively.

[5]Combined silt and clay percentages.

[6]HAS, high-altitude snowmelt; LAR, low-altitude rain; LARS, low-altitude rain and snowmelt; LAS, low-altitude snowmelt; MAS, medium-altitude snowmelt; MHAS, medium- to high-altitude snowmelt; R, rain; RHAS, receding high-altitude snowmelt; and SLF, seasonal low flow.

[7]Estimated.

Incline and Third Creeks ranged from 0.6 to 110 ft^3/s (table 4), and measured sediment discharge ranged from 0.006 to 1,420 t/d (table 7).

Measured ranges of nutrient concentrations and discharges for Third and Incline Creeks are listed in table 13. The table also indicates nutrient-transport ranges measured for Glenbrook Creek (fig. 1) during a similar study (Glancy, 1977). The Glenbrook data are included here for comparison with those of the Incline Village creeks. The tabulation shows that nutrient-concentration ranges are apparently similar for most constituents in the creeks, with the following exceptions: (1) the maximum measured concentration of total ammonium was considerably less for Glenbrook Creek than for the Incline Village creeks; (2) the maximum measured concentration of particulate organic nitrogen for Third Creek was considerably less than that for Incline and Glenbrook Creeks; (3) the minimum concentration of dissolved silica for Glenbrook Creek was noticeably greater than for the Incline Village creeks; and (4) the maximum measured concentration of total organic carbon for Incline Creek was markedly greater than for Third and Glenbrook Creeks. Other than these noted exceptions, the measured concentration ranges for the three streams are similar.

The nutrient-study strategy was not intended to document seasonal or long-term changes in concentrations or transport rates. Because the data purposely were collected mainly during periods of intense sediment transport, detailed analyses to detect seasonal or long-term trends are not practicable. Field nutrient-collection procedures and laboratory analytical schemes varied somewhat during the study period; as a result, some constituents were determined for only 1 or 2 years of the study. Thus, the data are inherently uneven and in many ways not amenable to seasonal and long-term trend analyses. However, in spite of the deterrents to trend analyses, cursory examinations of data for Third and Incline Creeks suggest certain trends. These trends are detailed in table 13 and summarized below:

(1) Dissolved-nitrate concentrations seem to have been generally higher during March than during other months. However, this characteristic does not extend to dissolved-nitrate discharge.
(2) Concentrations and discharges of both total and dissolved ammonium were generally lower in 1973 than during previous study years.
(3) Concentrations and discharges of dissolved orthophosphate were generally greater during 1969–71 than during 1972 and 1973.

The tentative study-period trends of ammonium and orthophosphate suggest accelerated nutrient movement during early phases of urban development when effects of land clearing and road construction may have triggered higher-than-normal nutrient releases from freshly disturbed surficial earth materials. However, such an implication is tenuous at best because of the insufficient and uneven distribution of the nutrient data.

A comparison of measured nutrient-discharge ranges of the Incline Village creeks with Glenbrook Creek (table 13) shows one persistent trend—maximum measured discharges of almost all nutrient species from Glenbrook Creek are considerably less than those of the Incline Village creeks. The most obvious reason for this difference is that Glenbrook Creek generally carries considerably less water than Third and Incline Creeks and thus generally transports smaller quantities of nutrients.

The ranges of concentrations and discharges listed in table 13 suggest that nutrient movement by Third and Incline Creeks to Lake Tahoe can be generally categorized as follows: (1) transport of dissolved nitrite is generally less than that of other nitrogen species; (2) transport of dissolved nitrate and ammonium are similar in magnitude; and (3) in terms of weight quantity, total organic nitrogen is the major nitrogen component moving to the lake.

Relations Among Movement of Nutrients, Water, and Sediment

Graphical Relations

Nutrient movements by Third and Incline Creeks near their mouths were analyzed graphically. Graphical plots of nutrient-transport rates versus concurrent rates of streamflow and sediment transport showed apparent relations among movements of nutrients, water, and sediment. The graphs were rated visually as to the degree of apparent correlation among the three variables. The apparent correlations for about 120 such graphs have been rated in table 14 on the basis of the following criteria:

(1) Excellent (E). Sharp, well-defined alinement trend. Virtually no scatter of points from trend line. Almost all points are intercepted by trend line.
(2) Good (G). Sharp, well-defined alinement trend. Only slight scatter of points from trend line. Points generally converge at upper ends of log scales. Almost all points fall on or near the trend line.
(3) Fair (F). Obvious and definite alinement trend. Moderate scatter of points. Point scatter at upper end of log scales generally less than scatter at lower end. A moderate number of points appear unrelated to trend line.
(4) Poor (P). Vague to moderate alinement trend. Great scatter of points about trend line. Scatter also wide at upper end of log scales.
(5) Very Poor (VP). Little or no alinement trend. Great scatter of all or most points.

Table 13. Measured ranges of nutrient concentrations and discharges for Third, Incline, and Glenbrook Creeks near their mouths
[Periods of record: Third and Incline Creeks, water years 1970–73; Glenbrook Creek, water years 1972–74]

Nutrient[1]	Measured concentration range (milligrams per liter)			Measured discharge range (pounds per day)		
	Third Creek	Incline Creek	Glenbrook Creek	Third Creek	Incline Creek	Glenbrook Creek
Nitrate, dissolved	0.00–0.25	0.00–0.15	0.01–0.36	0.0–30	0.0–15	0.1–14
Nitrite, dissolved	0.00–0.02	0.00–0.05	0.00–0.02	0.0–1	0.0–3	0.0–0.8
Ammonium, total	0.00–1.1	0.01–1.2	0.00–0.24	0.0–40	1.0–72	0.0–8.2
Ammonium, dissolved	0.01–0.17	0.00–0.13	0.01–0.10	0.0–30	0.0–13	0.04–4
Organic nitrogen, total	0.06–3.5	0.05–2.6	0.22–1.6	0.6–410	1–310	0.68–54
Organic nitrogen, particulate	0.02–0.79	0.00–1.4	0.03–1.2	0.2–310	0.0–250	0.2–41
Organic nitrogen, dissolved	0.02–0.42	0.00–0.44	0.08–0.38	0.4–100	0.0–58	0.39–13
Nitrogen, total	0.08–3.8	0.15–2.9	0.25–2.1	0.9–450	5.8–330	0.87–71
Nitrogen, dissolved	0.06–0.69	0.13–0.59	0.23–0.78	0.6–140	3.2–68	0.58–27
Phosphorus, total	0.04–0.65	0.04–0.83	0.06–0.54	0.4–190	1–100	0.27–18
Phosphorus, particulate	0.00–0.46	0.00–0.78	0.01–0.53	0.0–190	0.0–97	0.1–18
Phosphorus, dissolved	0.01–0.10	0.01–0.07	0.01–0.10	0.4–5.9	0.5–6	0.2–2
Orthophosphate, dissolved	0.00–0.25	0.01–0.35	0.00–0.10	0.0–13	0.4–26	0.0–2
Silica, dissolved	11–18	13–24	19–24	190–4,900	480–3,100	58–780
Organic carbon, total	1.0–17	2.0–27	3.0–18	11–6,600	40–3,500	11–610

[1]All concentrations and discharges for nitrogen and phosphorus species are expressed in terms of the elements N and P, respectively.

Examples of the different classes of ratings are shown in figures 29 through 33. Figure 29, a graph of particulate phosphorus versus fine-grained sediment load for Incline Creek, depicts an excellent correlation rating; figures 30, 31, 32, and 33 depict good, fair, poor, and very poor graphical correlation ratings, respectively. The plots indicate that most nutrient loads moving to the lake generally tend to increase as water discharge and sediment transport increase. However, the generally poor graphical correlations between most nutrient species and streamflow or sediment transport suggest that nutrient movement is probably influenced by many other factors. Obviously, more work is needed to define the other influential parameters and to quantify their specific effects.

Statistical Relations

The nutrient, water, and sediment data of table 12, which form the bases for the graphical correlation ratings of table 14, also were analyzed statistically. Table 15 summarizes results of linear-regression analyses of relations among nutrient, water, and sediment transport for Third and Incline Creeks. Two factors constrain the validity and interpretive value of the linear-regression analyses. (1) Figures 30–33 and the many other graphs forming the basis of table 14 suggest that many of the relations may be curvilinear rather than linear. (2) The data comprise, at most, 23 samples for Third Creek and 19 samples for Incline Creek collected over a 4-year period (representing only about 5 percent of the total number of sediment samples collected at the sites) and, therefore, are too few to guarantee statistical significance. Therefore, the summary results in table 15 are intended mainly to supplement the graphical categorizations summarized in table 14. The quantitative nature of the statistical data also allows easier comparisons between nutrient-transport trends of this study and those for Glenbrook Creek (fig. 1).

The statistical scheme for analyzing the data is similar to that used in studying water-sediment transport relations described earlier in the Sediment Transport section. However, in this instance, the analyses test four independent variables (water discharge, total-sediment load, coarse-grained sediment load, and fine-grained sediment load) against 14 dependent variables (the nutrient species shown in the first column of table 15).

Table 16 is the summary of statistical analyses for nutrient transport for Glenbrook Creek (Glancy, 1977, p. 39). It is reproduced here to allow comparisons between the Incline Village area and the Glenbrook basin. These comparisons improve perspective on nutrient-transport characteristics for both study areas.

The statistical data in table 15 show that nutrient transport by Third and Incline Creeks is directly related to the movements of both water and sediment. In short, as streamflow and sediment-transport rates increase, nutrient-movement rates also increase. The correlation coefficients strongly suggest that nutrient movements correlate better with sediment transport than with water discharge. This should be expected of particulate nutrient species, such as particulate organic nitrogen and particulate phosphorus, which are components of the sediment being transported. However, most dissolved nutrient species (silica excluded) also appear to correlate better with sediment than with water. These tendencies are also generally true for Glenbrook Creek (table 16). This persistent trend supports the contention that erosion and nutrient transport to the lake are related. However, the

Table 14. Summary of graphical correlations among water discharge, sediment transport, and nutrient transport to Lake Tahoe for Third and Incline Creeks

Correlated parameter[2]	Correlation for Third Creek[1]				Correlation for Incline Creek[1]			
	Water discharge	Total sediment discharge	Coarse-grained sediment discharge[3]	Fine-grained sediment discharge[4]	Water discharge	Total sediment discharge	Coarse-grained sediment discharge[3]	Fine-grained sediment discharge[4]
Water discharge	—	F	F	P	—	F	F	P
Dissolved nitrate discharge[5]	P	P	P	P	VP–P	P	P	VP
Dissolved nitrite discharge[5]	VP	VP	VP	VP	VP	VP	VP	VP
Total ammonium discharge[5]	VP	VP	VP	VP	VP	VP–P	VP	VP
Dissolved ammonium discharge[5]	P	VP	VP–P	P–F	P–F	VP–P	VP	VP
Total organic nitrogen discharge	P–F	P–F	P	P	F	P–F	P	VP–P
Particulate organic nitrogen discharge	P–F	P–F	P	P–F	P–F	P	VP–P	P–F
Dissolved organic nitrogen discharge	P	P	P	P	P–F	P	P	P
Total nitrogen discharge	P	F	P–F	P–F	P–F	P–F	P	P
Dissolved nitrogen discharge	P–F	P–F	P	P–F	P–F	P	P	P–F
Total phosphorus discharge	F	F	P–F	P–F	P	F	P	P–F
Particulate phosphorus discharge	F	P	VP–P	F	P	P	VP	E
Dissolved phosphorus discharge[5]	P	F	P–F	P	VP–P	P	VP–P	F
Dissolved orthophosphate discharge[5]	P	P	P	VP	VP–P	VP–P	VP–P	P
Dissolved silica discharge	G	F	F–G	P	G	F	F	P
Total organic carbon discharge[5]	P–F	F	F	P–F	F	F–G	P	F

[1] Correlation ratings: VP, very poor; P, poor; F, fair; G, good; and E, excellent. Rating criteria are described in text.
[2] All discharges for nitrogen and phosphorus species are expressed in terms of the elements N and P, respectively.
[3] Coarse-grained sediment comprises sand and gravel (particle diameter greater than 0.062 mm).
[4] Fine-grained sediment comprises silt and clay (particle diameter less than 0.062 mm).
[5] Many reported concentrations are at or below lower limits of accurate determination; these limits may contribute to poorness of correlations.

often numerically small correlation coefficients suggest that, for most nutrient species, the relations between erosion and nutrient transport are probably quite complex. That correlations between nutrients and sediment transport are even better for Glenbrook Creek than for Third and Incline Creeks suggests that this relation is better defined in minimally developed areas than in areas undergoing heavy development.

Glenbrook Creek regression equation exponents are much larger than those of Third and Incline Creeks for relations of both water and sediment movement to nitrate, total ammonium, and particulate phosphorus. This difference implies that transport of these nutrient species in Glenbrook Creek is more sensitive to changes in water and sediment movement than it is in the Incline Village creeks. A comparison of nutrient-transport correlation coefficients of Third and Incline Creeks with those of Glenbrook Creek shows the Glenbrook coefficients to be noticeably greater overall.

Statistical relations between transport of nutrients and movements of water and sediment appear to be best for Glenbrook Creek, intermediate for Third Creek, and poorest for Incline Creek. Incline Creek has the most, and Glenbrook Creek the least development in terms of percentage of total basin area. Thus, the statistical data suggest that the degree of correlation of relations between fluvial-nutrient transport and the movements of water and sediment appears to depend at least in part on the degree

Table 15. Summary of linear-regression analyses of water discharge, sediment transport, and nutrient transport to Lake Tahoe by Third and Incline Creeks

Third Creek

Dependent variables *(y)*	Independent variables *(x)*							
	Water discharge				Total sediment discharge			
Nutrient and sediment discharges[1]	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)
Nitrate, dissolved	20	$y=0.86x^{0.62}$	0.57	0.37	20	$y=1.5x^{0.36}$	0.79	0.27
Ammonium, total	20	$y=1.5x^{0.61}$	.46	.54	20	$y=2.6x^{0.34}$	.63	.48
Ammonium, dissolved	15	$y=0.24x^{1.0}$	.74	.45	15	$y=1.3x^{0.42}$	.90	.29
Organic nitrogen, total	20	$y=1.8x^{0.25}$	.79	.39	20	$y=8.8x^{0.46}$	.91	.27
Organic nitrogen, particulate	14	$y=0.37x^{1.4}$	.81	.50	14	$y=4.1x^{0.55}$	.94	.30
Organic nitrogen, dissolved	16	$y=0.53x^{1.05}$	.75	.45	16	$y=3.8x^{0.37}$	.76	.44
Nitrogen, total	20	$y=3.6x^{0.97}$	.75	.40	20	$y=14x^{0.44}$	.93	.23
Nitrogen, dissolved	14	$y=1.0x^{1.04}$	.82	.34	14	$y=6.7x^{0.38}$	.89	.27
Phosphorus, total	22	$y=0.57x^{1.2}$	.83	.38	22	$y=3.7x^{0.51}$	.95	.21
Phosphorus, particulate	9	$y=0.18x^{0.74}$	.76	.51	9	$y=2.0x^{0.55}$	.90	.34
Phosphorus, dissolved	11	$y=0.55x^{0.48}$	.72	.25	11	$y=1.3x^{0.19}$	.87	.18
Orthophosphate, dissolved	20	$y=0.87x^{0.42}$	.44	.40	20	$y=1.3x^{0.25}$	.73	.30
Silica, dissolved	16	$y=110x^{0.87}$	.99	.043	16	$y=600x^{0.27}$	.86	.20
Organic carbon, total	12	$y=12x^{1.3}$	.87	.38	12	$y=140x^{0.48}$	.97	.19
Sediment load, total	23	$y=0.025x^{2.4}$	.89	.55				

Dependent variables *(y)*	Independent variables *(x)*							
	Coarse-grained sediment discharge				Fine-grained sediment discharge			
Nutrient discharge[1]	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)
Nitrate, dissolved	18	$y=2.5x^{0.25}$	0.63	0.29	18	$y=2.6x^{0.43}$	0.68	0.27
Ammonium, total	18	$y=8.7x^{0.08}$	.19	.37	18	$y=7.5x^{0.21}$	.31	.36
Ammonium, dissolved	13	$y=3.3x^{0.21}$	.56	.30	13	$y=1.5x^{0.64}$	.91	.15
Organic nitrogen, total	17	$y=14x^{0.36}$	.80	.26	17	$y=13x^{0.57}$	.75	.28
Organic nitrogen, particulate	12	$y=13x^{0.35}$	.71	.31	12	$y=11x^{0.62}$	.78	.27
Organic nitrogen, dissolved	14	$y=5.0x^{0.32}$	.56	.47	14	$y=6.1x^{0.47}$	.49	.49
Nitrogen, total	17	$y=28x^{0.28}$	.80	.20	17	$y=29x^{0.47}$	.78	.21
Nitrogen, dissolved	12	$y=12x^{0.25}$	.64	.29	12	$y=13x^{0.42}$	.67	.28
Phosphorus, total	19	$y=6.5x^{0.40}$	.86	.28	19	$y=4.7x^{0.86}$	.94	.18
Phosphorus, particulate	8	$y=2.2x^{0.54}$	.80	.41	8	$y=3.5x^{0.92}$	.95	.21
Phosphorus, dissolved	9	$y=1.9x^{0.11}$	.52	.18	9	$y=2.0x^{0.20}$	.61	.17
Orthophosphate, dissolved	17	$y=1.9x^{0.16}$	.44	.30	17	$y=1.7x^{0.36}$	.66	.25
Silica, dissolved	14	$y=480x^{0.36}$	.92	.15	14	$y=840x^{0.30}$	.51	.31
Organic carbon, total	10	$y=270x^{0.36}$	.87	.22	10	$y=280x^{0.62}$	.86	.22

Table 15. Summary of linear-regression analyses of water discharge, sediment transport, and nutrient transport to Lake Tahoe by Third and Incline Creeks—Continued

Incline Creek

Dependent variables *(y)*	Independent variables *(x)*							
	Water discharge				Total sediment discharge			
Nutrient and sediment discharges[1]	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)
Nitrate, dissolved	17	$y=1.2x^{0.57}$	0.39	0.35	17	$y=2.8x^{0.24}$	0.57	0.31
Ammonium, total	19	$y=4.0x^{0.32}$	.14	.54	19	$y=3.7x^{0.36}$	.57	.45
Ammonium, dissolved	11	$y=0.11x^{1.2}$	.63	.42	11	$y=0.97x^{0.39}$	.66	.41
Organic nitrogen, total	18	$y=0.28x^{1.8}$	.78	.36	18	$y=7.6x^{0.57}$	.87	.28
Organic nitrogen, particulate	11	$y=0.20x^{1.7}$	.74	.49	11	$y=4.5x^{0.62}$	.82	.41
Organic nitrogen, dissolved	12	$y=1.8x^{0.78}$	.59	.25	12	$y=7.1x^{0.28}$	.67	.23
Nitrogen, total	18	$y=2.3x^{1.2}$	.66	.35	18	$y=18x^{0.46}$	.87	.23
Nitrogen, dissolved	11	$y=1.1x^{1.1}$	.82	.21	11	$y=9.6x^{0.32}$	.91	.16
Phosphorus, total	17	$y=0.52x^{1.3}$	.62	.43	17	$y=4.3x^{0.52}$	.87	.27
Phosphorus, particulate	8	$y=0.72x^{0.99}$	.37	.57	8	$y=2.9x^{0.56}$	.76	.40
Phosphorus, dissolved	10	$y=0.47x^{0.56}$	.52	.28	10	$y=1.4x^{0.21}$	.68	.24
Orthophosphate, dissolved	18	$y=1.4x^{0.33}$	.15	.53	18	$y=1.3x^{0.36}$	.60	.43
Silica, dissolved	14	$y=160x^{0.84}$	.97	.58	14	$y=940x^{0.16}$	.63	.18
Organic carbon, total	10	$y=11x^{1.5}$	.75	.40	10	$y=190x^{0.56}$	.94	.20
Sediment load, total	19	$y=0.019x^{2.5}$	.71	.61				

Dependent variables *(y)*	Independent variables *(x)*							
	Coarse-grained sediment discharge				Fine-grained sediment discharge			
Nutrient discharge[1]	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)
Nitrate, dissolved	14	$y=5.2x^{0.077}$	0.18	0.28	14	$y=5.8x^{0.028}$	0.057	0.28
Ammonium, total	16	$y=11x^{0.021}$	.026	.50	16	$y=3.6x^{0.57}$	.61	.39
Ammonium, dissolved	10	$y=2.9x^{0.018}$	.034	.42	10	$y=2.1x^{0.23}$	.27	.40
Organic nitrogen, total	15	$y=19x^{0.34}$	.59	.30	15	$y=20x^{0.35}$	.52	.32
Organic nitrogen, particulate	10	$y=12x^{0.38}$	.52	.50	10	$y=6.6x^{0.86}$	.84	.32
Organic nitrogen, dissolved	11	$y=9.4x^{0.24}$	.61	.24	11	$y=10x^{0.26}$	.46	.27
Nitrogen, total	15	$y=40x^{0.25}$	.53	.26	15	$y=33x^{0.37}$	.67	.23
Nitrogen, dissolved	9	$y=18x^{0.15}$	.57	.18	9	$y=20x^{0.13}$	.33	.21
Phosphorus, total	14	$y=8.7x^{0.36}$	.56	.36	14	$y=5.3x^{0.65}$	.86	.22
Phosphorus, particulate	7	$y=4.0x^{0.49}$	.37	.52	7	$y=4.3x^{0.85}$	.99	.086
Phosphorus, dissolved	8	$y=1.4x^{0.22}$	.37	.23	8	$y=1.6x^{0.31}$	.75	.17
Orthophosphate, dissolved	15	$y=1.7x^{0.32}$	.41	.46	15	$y=0.82x^{0.70}$	.76	.33
Silica, dissolved	12	$y=1000x^{0.17}$	.56	.17	12	$y=2900x^{-0.064}$	.17	.20
Organic carbon, total	8	$y=470x^{0.32}$	.63	.30	8	$y=390x^{0.51}$	.79	.24

[1]All discharges for nitrogen and phosphorus species are expressed in terms of the elements N and P, respectively.

Table 16. Summary of linear-regression analyses of water discharge, sediment transport, and nutrient transport to Lake Tahoe by Glenbrook Creek

Dependent variables (*y*)	Independent variables (*x*)							
	Water discharge				Total sediment discharge			
Nutrient and sediment discharges[1]	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)	Sample size (number of data points)	Regression equation	Correlation coefficient	Standard error of estimate for dependent variable (log units)
Nitrate, dissolved	9	$y=0.22x^{1.5}$	0.81	0.50	9	$y=1.6x^{0.62}$	0.83	0.48
Ammonium, total	8	$y=0.27x^{1.5}$	.91	.30	8	$y=1.9x^{0.70}$	.94	.24
Ammonium, dissolved	9	$y=0.13x^{1.3}$	.84	.37	9	$y=0.72x^{0.54}$	.88	.33
Organic nitrogen, total	9	$y=1.7x^{1.5}$	.97	.19	9	$y=13x^{0.62}$	.97	.17
Organic nitrogen, particulate	9	$y=0.57x^{1.9}$	.94	.33	9	$y=7.6x^{0.80}$	.96	.28
Organic nitrogen, dissolved	9	$y=0.91x^{1.1}$	.91	.23	9	$y=4.0x^{0.46}$	.94	.20
Nitrogen, total	9	$y=2.2x^{1.6}$	.97	.18	9	$y=18x^{0.64}$	.98	.13
Nitrogen, dissolved	9	$y=1.4x^{1.3}$	.96	.16	9	$y=7.6x^{0.52}$	.98	.12
Phosphorus, total	9	$y=0.58x^{1.5}$	.95	.22	9	$y=4.4x^{0.63}$	.98	.13
Phosphorus, particulate	7	$y=0.17x^{2.1}$	.99	.19	7	$y=3.0x^{0.90}$	.98	.22
Phosphorus, dissolved	7	$y=0.24x^{0.66}$	.75	.31	7	$y=0.62x^{0.28}$	.74	.32
Orthophosphate, dissolved	8	$y=0.19x^{0.67}$	.72	.32	8	$y=0.48x^{0.27}$	.71	.33
Silica, dissolved	8	$y=120x^{0.93}$	.999	.016	8	$y=400x^{0.37}$	.97	.098
Organic carbon, total	7	$y=27x^{1.5}$	.98	.14	7	$y=190x^{0.60}$	.99	.044
Total sediment load	9	$y=0.072x^{2.4}$	.98	.25				

[1] All discharges for nitrogen and phosphorus species are expressed in terms of the elements N and P, respectively.

of drainage-basin development. However, natural drainage characteristics of the three basins are quite different except for overall similarities in basin areas. Thus, the differences in statistical relations may be caused, at least in part, by natural differences among the drainages.

Further examination of nutrient-sediment transport correlation coefficients for Third and Incline Creeks shows that fine-grained sediment apparently correlates better with nutrient transport than does coarse-grained sediment in about two-thirds of the regression analyses. This infers that, in general, nutrient movement may be more closely related to fine-grained sediment movement; however, many of the differences between correlation coefficients for coarse- and fine-grained sediment are only slight. These slight differences, coupled with the inherent deficiencies of this statistical analysis, suggest that caution should be used in interpreting the significance of these apparent differences. A more conclusive interpretation will require additional data.

Regression-equation exponents (table 15) for relations between fine-grained sediment and nutrients are generally larger (13 of 14 for Third Creek and 11 of 14 for Incline Creek) than those for coarse-grained sediment versus nutrients. This difference implies that nutrient transport is more sensitive to the movement of fine-grained sediment.

Comparison of Graphical and Statistical Analyses

The graphical and statistical analyses of nutrient transport by Third and Incline Creeks are analytical techniques that are semi-independent of each other. The graphical technique is semiquantitative, and the interpretive results depend to a large degree on the subjective judgment of the interpreter regarding the placement of a curve that defines the relation suggested by the data plots. The interpreter subsequently rates the quality of the relation subjectively by assessing the degree of scatter of the plotted data points about the curve. In contrast, the statistical linear-regression analysis objectively derives a straight-line equation that represents the best fit of the straight line that describes the relation according to prescribed mathematical theory. Thus, combined use of both techniques allows comparisons of subjective and objective analyses, both of which have benefits and liabilities regarding a proper understanding of nutrient transport.

A general comparison of the results suggests that, in about two-thirds of the cases, both techniques give similar results. In the remaining one-third of the cases, the two analytical techniques yield results that are sharply divergent; the reasons for this divergence are unclear to the author—particularly because the statistical approach,

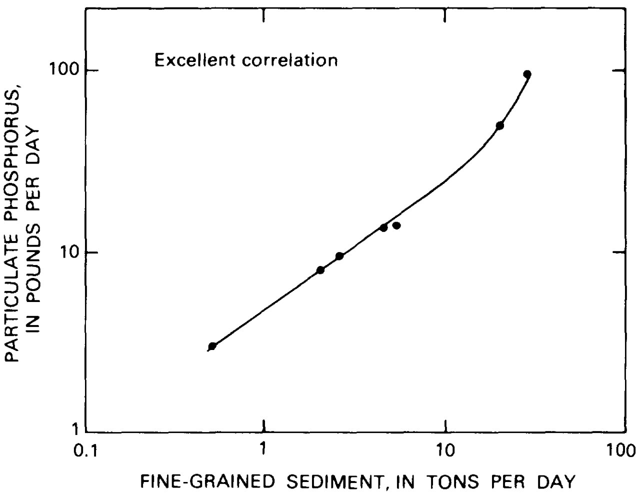


Figure 29. Relation of discharges of fine-grained sediment to particulate phosphorus for Incline Creek near its mouth.

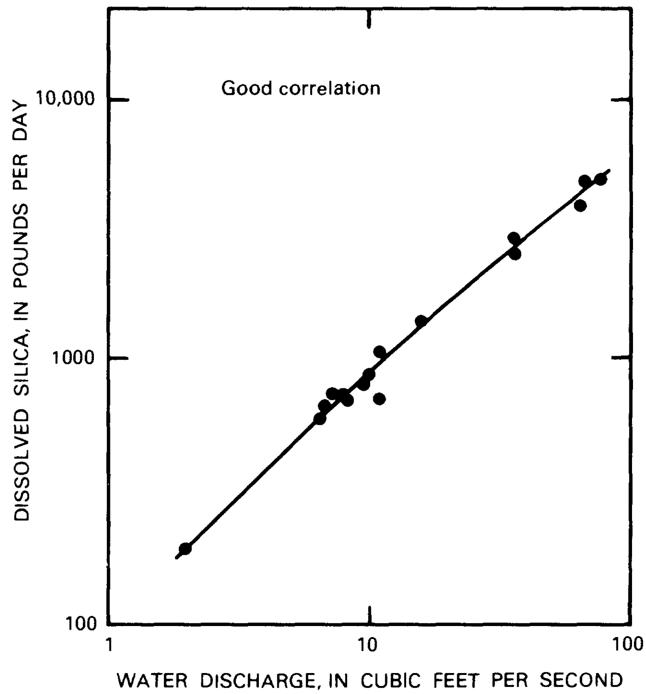


Figure 30. Relation of discharges of water to dissolved silica for Third Creek near its mouth.

which is the least flexible method, paradoxically tends to give superior correlation results in a majority of the divergent cases. Possible inherent deficiencies in the quantity and quality of the available nutrient data and the reconnaissance nature of this study preclude resolution of these differences.

The significance of both graphically and statistically inferred relations between sediment and nutrient transport should be tempered by the dependence of both sediment and nutrient loads on water discharge. This close relation does not necessarily invalidate the correlations, but the apparent correlations do not necessarily guarantee strict cause-and-effect relations between the movement of nutrients and sediment.

In summary, both graphical and statistical analyses show varying relations among fluvial-nutrient transport, stream discharge, and fluvial-sediment transport. However, available data do not quantitatively define these relations with sufficient accuracy to allow dependable prediction of nutrient movements to Lake Tahoe solely on the basis of quantitative knowledge of streamflow and sediment transport.

SUMMARY OF FINDINGS

Streamflow

From the study area, most of the runoff (and sediment transport) to the lake comes from five perennially flowing tributaries, and their combined drainage area of 17.8 mi^2 makes up about 80 percent of the 21.9-mi^2 study area. Annually, the five-stream composite runoff ranged from 9,600 to 17,600 acre-ft and cumulatively furnished 59,000 acre-ft of surface flow to the lake. Individual creeks ranged in annual runoff from 460 to 7,070 acre-ft, and their instantaneous water discharges ranged between 0.2 to 110 ft^3/s.

Snowmelt runoff was the major volumetric runoff component of the annual flow of the five principal creeks. Peak instantaneous streamflows each year during the study were caused by snowmelt, but regional hydrologic knowledge and hydrologic history of the study area suggest that exceptionally large discharges sometimes occur from thunderstorm-caused flash floods, mainly during nonwinter months.

Third and Incline Creeks, the largest creeks, although of similar drainage size and adjacent to each other, exhibited markedly different runoff characteristics (and different sediment-transport characteristics). A major cause of these differences is the striking dissimilarity in the area-altitude distributions of the two drainages.

Sediment Transport

The annual five-stream cumulative sediment transport to the lake during the study ranged from 1,500 to 11,000 t and cumulated to a study-period total of 31,000 t, about 90 percent of which was delivered by snowmelt runoff and about 10 percent by rainfall and low-flow runoff. Annually, individual-stream sediment transport

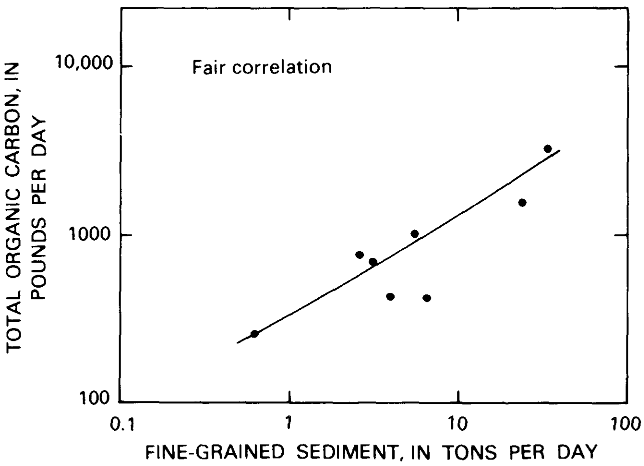


Figure 31. Relation of discharges of fine-grained sediment to total organic carbon for Incline Creek near its mouth.

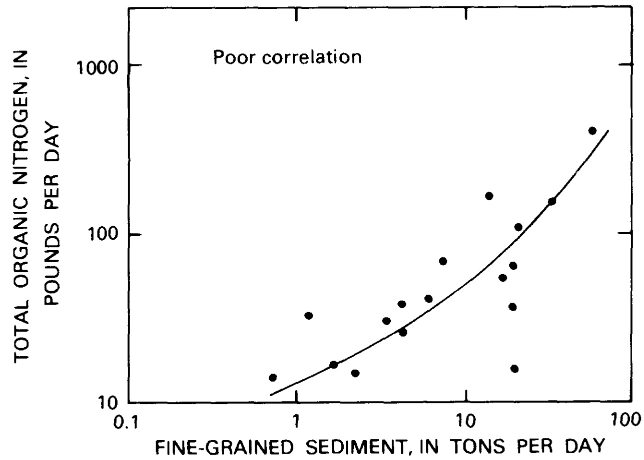


Figure 32. Relation of discharges of fine-grained sediment to total organic nitrogen for Third Creek near its mouth.

ranged from 20 to 5,200 t. For comparison, a brief flash flood of Second Creek, one of the five streams, transported about 75,000 t from about 0.5 mi^2 of its drainage in less than 1 hour during the summer of 1967; that quantity is about 2½ times the sediment moved to the lake by all five principal creeks during this 4-year study.

Instantaneous measured sediment concentrations during the study ranged from 1 to 13,200 mg/L, and discharges ranged from 0.001 to 1,420 t/d near the mouths of the five creeks. Concentrations ranging up to 63,200 mg/L were measured at upstream tributary sites.

Estimated annual sediment yields from undeveloped areas of the principal drainages ranged from 3 to 930 t/mi^2; whereas those from developed areas ranged from 26 to 5,000 t/mi^2. Sediment yields from developed areas averaged about 10 times those from undeveloped areas for the overall study period.

Composition of the cumulative study-period sediment load transported to the lake by the five principal creeks was about 75 percent sand and gravel (mostly sand), 15 percent silt, and 10 percent clay. Suspended sediment probably constituted considerably less than half the total sediment transported to the lake by the five creeks. The coarse-grained nature of the cumulative 4-year five-creek sediment load suggests that turbidity (a visual effect caused mainly by sediment particles finer grained than sand) is a poor indicator of total-sediment-load transport at Incline Village. Thus, the human eye cannot accurately perceive the overall movement of sediment to the lake by streams.

Changes in annual runoff rates of individual creeks caused much greater changes in magnitudes of sediment transport; thus, mathematically, sediment transport was exponentially related to runoff as follows:

$$Q_s = C(Q_w)^x,$$

where

Q_w = water discharge, independent variable,
C = a numerical constant,
Q_s = sediment discharge, and
x > 1.

Statistical analyses of sediment transport showed coarse-grained (sand and gravel) sediment to be more correlative with varying magnitudes of water discharge than fine-grained (silt and clay) sediment. Linear-regression analyses produced mathematical equations relating water discharge and sediment transport that are generally inaccurate models for predicting sediment transport; the equations are, however, enlightening and instructive regarding sediment-transport processes.

Field experiences in tracking sediment movement within developed areas showed that most sources of sediment input to creeks were generally identifiable as point sources and were thus amenable to rehabilitative control. Of the many specific and general sources of sediment noted during the study, roadways were the most obvious and widespread sources of fluvial sediment throughout the developed areas.

Flash floods in Third and Second Creeks during 1965 and 1967, respectively (before the onset of this study), disrupted channel stability of these creeks. The resultant instability accelerated sediment yields from undeveloped areas of these drainages that persisted throughout this study.

General field observations of sediment movement and analyses of field data throughout this study suggest that fluvial-sediment transport can be best managed by controlling the availability of sediment for transport and (or) by controlling the flow of water necessary to move the available sediment.

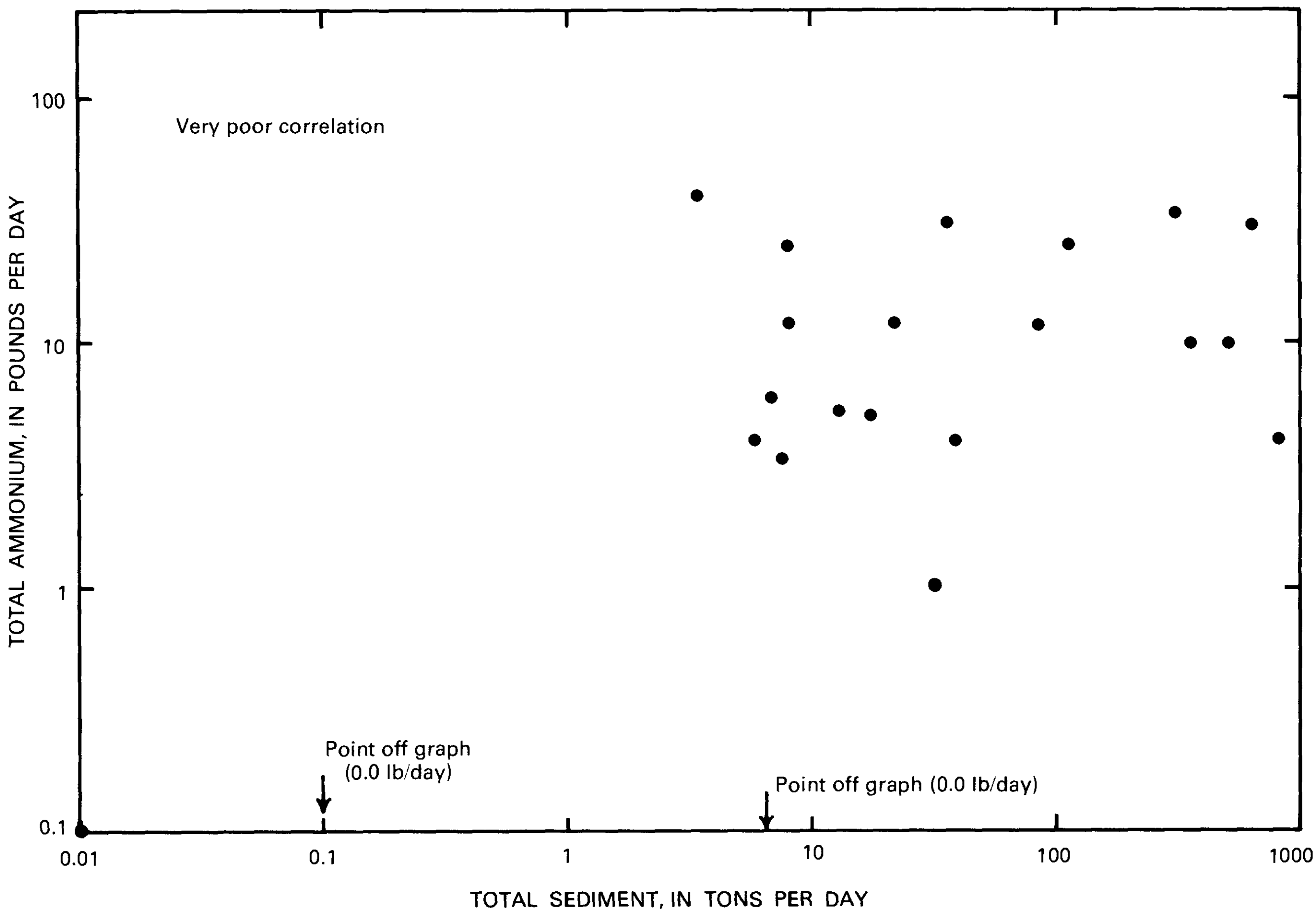


Figure 33. Relation of discharges of total sediment to total ammonium for Third Creek near its mouth.

Nutrient Transport

The limited preliminary data indicate that relations between nutrient transport and the movement of water-sediment mixtures are complex. Nutrient studies were concentrated on Third and Incline Creeks; they showed that nutrient-transport rates (loads) for these creeks generally increased as water-discharge and sediment-transport rates increased. Measured ranges of concentrations for specific nutrient species were generally similar in both creeks. Knowledge of nutrient contributions to Lake Tahoe by Third and Incline Creeks gained during the study can be summarized as follows: (1) Particulate phosphorus was the dominant component of total phosphorus moving to the lake, whereas dissolved phosphorus and dissolved orthophosphate generally contributed similar but lesser amounts of phosphorus than particulate phosphorus. (2) Organic nitrogen constituted the bulk of nitrogen moving to the lake. (3) Transport rates for dissolved nitrate and ammonium were of similar magnitude. (4) Nitrite transport was generally less than that of other nitrogen species.

Graphical plots of nutrient transport versus water-sediment movement showed that correlations were generally poor, as confirmed by statistical analyses, and some of the logarithmic graphical relations appeared to be nonlinear. Statistical analyses of nutrient transport rates versus those of the water-sediment mixture suggested that (1) nutrient-transport correlations with sediment transport were better than those with water discharge, (2) nutrient transport by Third Creek appeared to be slightly better related to water and sediment movement than that of Incline Creek, (3) fine-grained sediment transport appeared to correlate better with nutrient transport than coarse-grained sediment transport for both Third and Incline Creeks, and (4) nutrient transport of Third and Incline Creeks is generally more sensitive to the movement of fine-grained sediment than of coarse-grained sediment.

Because of a lack of any predevelopment data on nutrient transport, there is no indication whether transport during the study period was greater than, less than, or similar to that when development was less or nonexistent. Many additional data must be properly collected and analyzed before relations among movements of nutrients, water, and sediment for Incline Village area creeks can be satisfactorily understood.

CONSIDERATIONS FOR FUTURE STUDIES

This study was designed to (1) develop basic knowledge on a number of fundamental hydrologic parameters within the study area, (2) provide some local perspective on alleged or suspected basin-wide environmental problems, (3) demonstrate the technical and economic feasibility of acquiring certain types of essential hydrologic knowledge, (4) launch a first approximation effort to obtain worthwhile data on nutrient transport by streamflow, and (5) provide data and knowledge bases to allow and encourage more detailed and more efficient future studies.

Knowledge gained through this investigation provides guidelines for future studies as follows:

(1) A much more intensive field and analytical effort than carried on in this study would permit an accurate delineation of sediment inputs to the lake from varied specific sources within the developed areas.

(2) The streamflow data-collection activities would have to be continued over a period of years to permit predictions about the flow-duration characteristics of the streams.

(3) Additional data on particle-size distribution would permit a better understanding of the physical cause-and-effect relations between fluvial-sediment and nutrient transport.

(4) Characterization of the mineralogic and chemical makeup of sediment loads would permit a better assessment of the chemical impact of fluvial sediments on nutrient transport and general health of the streams and the lake.

(5) Additional data on streamflow, sediment transport, and nutrient transport, collected simultaneously, would permit a better understanding of the relations between lake eutrophication and sediment transport to the lake.

(6) Various data on stream biota would help define the stream ecosystems and document changes in these ecosystems.

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Metric Conversion Factors

Except for water-quality units of measure, only the inch-pound system is used in this report. For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below.

Multiply	By	To obtain
Acre	0.4047	Hectare (ha)
Acre-foot (acre-ft)	.001233	Cubic hectometer (hm^3)
Cubic foot per second (ft^3/s)	.02832	Cubic meter per second (m^3/s)
Cubic yard (yd^3)	7.645	Cubic meter (m^3)
Foot (ft)	.3048	Meter (m)
Foot per mile (ft/mi)	.1894	Meter per kilometer (m/km)
Inch (in.)	25.40	Millimeter (mm)
Mile (mi)	1.609	Kilometer (km)
Square mile (mi^2)	2.590	Square kilometer (km^2)
Ton, short	.9072	Metric ton (t)

Water-quality units of measure used in this report are as follows:

For concentration, milligrams per liter (mg/L), which are equivalent to parts per million for dissolved-solids concentrations less than about 7,000 mg/L.

For temperature, degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the formula $°F = [(1.8)(°C)] + 32$.

For specific conductance, micromhos per centimeter at 25 °C (μmho).

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