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EROSION PROCESSES, FLUVIAL SEDIMENT TRANSPORT, AND RESERVOIR SEDIMENTATION IN A PART OF THE NEWELL AND ZAYANTE CREEK BASINS SANTA CRUZ COUNTY, CALIFORNIA

By

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Prepared in cooperation with the
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PREFACE

The noteworthy adverse effects of urban sprawl in the San Francisco Bay region have prompted a sincere concern among planners and administrators about the relation between urbanization and the physical environment within which it develops. Significant among the factors in this relation are problems associated with water-resources management such as erosion control, flood protection, prevention of pollution, and the storage and use of water for recreational, municipal, and industrial purposes. In general, these problems are regional in nature but traditionally microcosmic in their analyses and attempted solutions, principally because the scope of the problems often transcends local jurisdiction. However, attempts are in progress by local, regional, and Federal agencies to consolidate fragmentary information on a regional scale for studies of the San Francisco Bay region.

This report is designed both to explore in detail the local problem situation and to be compatible at least in a conceptual manner with extensions to regional planning. The basins of Newell and Zayante Creeks are located in an area of rapid suburban expansion, and the problems that have occurred and may occur in these basins can be critical in planning decisions elsewhere in the Santa Cruz Mountains. The concepts and data presented herein should be applicable to several areas in the Santa Cruz Mountains westward from the San Andreas fault zone. In this region, measurements of the surficial processes of erosion and sedimentation are currently lacking, and the transfer of certain sediment data from other areas is precluded because of the geomorphic uniqueness of the region.

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EROSION PROCESSES, FLUVIAL SEDIMENT TRANSPORT, AND RESERVOIR SEDIMENTATION IN A PART OF THE NEWELL AND ZAYANTE CREEK BASINS SANTA CRUZ COUNTY, CALIFORNIA

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ABSTRACT

The drainage basins upstream from Loch Lomond, a water-supply reservoir on Newell Creek, and a proposed reservoir site on Zayante Creek were investigated for their characteristics with respect to the erosion, transportation, and deposition of sediment. The study area is underlain predominantly by sandstone, siltstone, and shale of Tertiary age that decompose readily into moderately deep soils, friable colluvium, and easily transported sediment particles. The Rices Mudstone and Twobar Shale Members of the San Lorenzo Formation of Brabb (1964) underlie steep dip slopes in the study area, and probably are the most highly erodible of the several geologic units present there. However, nearly all of the geologic units have shown a propensity for accelerated erosion accompanying the disturbance of the land surface by the roadbuilding practices that predominate over other types of sediment-producing land-use activities in the study area.

Sediment transport in the study area was estimated from (1) a reservoir survey of Loch Lomond in 1971 that was compared with a preconstruction survey of 1960, and (2) sampling of sediment transported in suspension by Zayante Creek during the 1970 and 1971 water years. At least 46 acre-feet of sediment accumulated in Loch Lomond in a 10-year period, and an unmeasured quantity of very fine sediment in the form of a thin layer over much of the reservoir bottom was observed. The measured quantity of deposited sediment in a 10-year period represented a sediment yield of about 1,100 tons annually per square mile of drainage basin upstream from the reservoir arms where the major deposition occurred. This sediment occupied less than 1 percent of the original capacity of Loch Lomond, but the volume of measured sediment deposition is probably conservative in view of the unmeasured deposits observed and a reservoir trap efficiency of about 95 percent.

Sediment sampling on Zayante Creek indicated suspended-sediment yields of about 4,570 and 570 tons per square mile for the 1970 and 1971 water years. These values were considered excessive with respect to the relatively low flows during which they were measured, and probably reflect the intensive and current roadbuilding practices in the central and upstream parts of the Zayante Creek drainage in the study area.

INTRODUCTION

The city of Santa Cruz (fig. 1) is experiencing difficulties with excessive sedimentation in Loch Lomond and anticipates problems with its planned reservoir on Zayante Creek (fig. 2). Loch Lomond, an 11-year old city water-supply reservoir, impounds water from Newell Creek about 8 miles north of Santa Cruz. Zayante reservoir will be about 2 miles east of Loch Lomond and will be in a drainage basin similar to that of Loch Lomond.

The U.S. Geological Survey, in cooperation with the city of Santa Cruz, began investigations in July 1970 to locate the major sources of sediment in the study area and to describe the types, mechanisms, and rates of sedimentation in Loch Lomond and the proposed Zayante reservoir. This project was planned as a 2-year study during which geology, topography, vegetation, soils, and land use were investigated in their relation to sedimentation. The project included the collection and analysis of sediment-discharge data on Zayante Creek and a reservoir survey of Loch Lomond. The data were obtained to determine the magnitude and extent of sediment deposition in Loch Lomond and to allow an estimation of the useful life expectancy for the proposed Zayante reservoir. Prior geologic, hydrologic, and other pertinent data were used to aid in the analysis of the erosion, transportation, and deposition of sediment

The purposes of this report are (1) to express the potential of the geologic units in the basin to contribute sediment to the proposed and existing reservoirs; (2) to summarize the land-use practices that might result in excessive erosion and consequent excessive sediment deposition; (3) to summarize and interpret the sediment-discharge and reservoir sedimentation data collected for this project; (4) to describe the sediment-transport characteristics of the streams in the study area; (5) to estimate the expected rate of sediment deposition in the proposed Zayante reservoir; and (6) to present the background information that may be desirable for future studies of sediment-related problems in the Santa Cruz Mountains.

This report was prepared by the U.S. Geological Survey in cooperation with the city of Santa Cruz as a part of investigations of the water resources of Santa Cruz County, California. Acknowledgment is due J. M. Knott of the Geological Survey for organization and direction of the reservoir survey of Loch Lomond and for supervision of the collection, analysis, and reduction of the reservoir sediment data. The project and report profited greatly from the assistance of L. E. Jackson, Jr., of the Geological Survey who performed both field and interpretive work on geology and reservoir sedimentation.

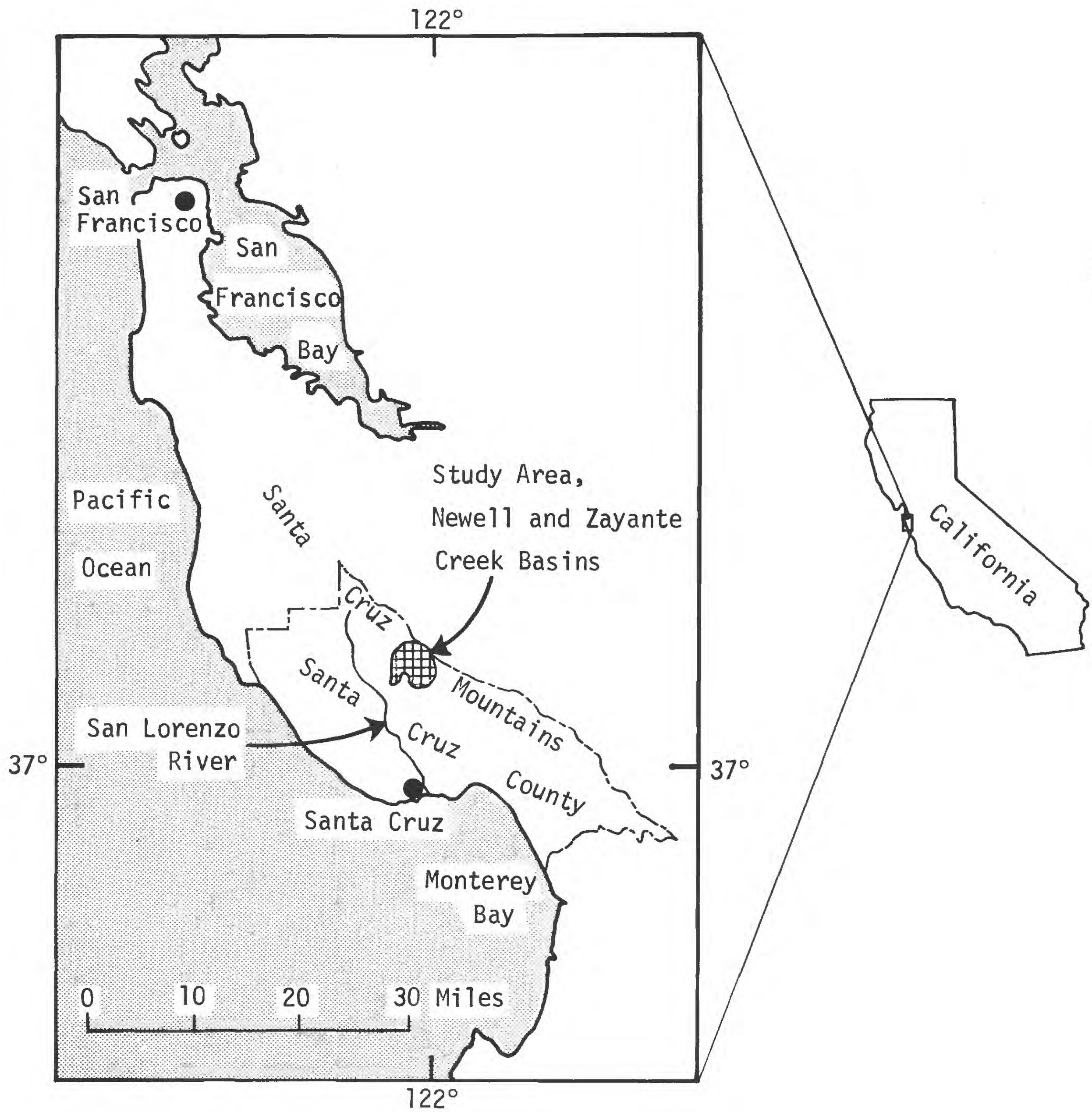


FIGURE 1.--Study area showing location of Newell and Zayante Creek basins.

PHYSICAL SETTING

Newell and Zayante Creeks drain an area of 36.7 square miles within the basin of the San Lorenzo River, which is the principal drainage for western Santa Cruz County (fig. 1). This report, however, is primarily concerned with the horseshoe-shaped unit of 18.0 square miles comprising the drainages of Newell and Zayante Creeks above Loch Lomond and the proposed Zayante reservoir (fig. 2). In this vicinity the terrain is rugged, characterized by V-shaped canyons having few areas of summit or valley flat. These valleys are geologically youthful and were probably formed by superposed streams which once flowed on an extensive erosion surface (Brabb, 1960 p. 11). Altitudes range from about 400 feet above mean sea level just downstream from Loch Lomond to above 2,400 feet at the northern tip of the Zayante Creek basin. Stream gradients average 230 feet per mile for Newell Creek and 250 feet per mile for Zayante Creek. The landscape is generally verdant, covered primarily by redwood forest and chaparral biotic communities; however, there are open, grassy hilltops, especially along the northern boundary of the study area, and a distinctive 50-acre grassy flat in the central part of the Zayante Creek basin. The climate is the moist Mediterranean climate characteristic of California's central coastal region where annual rainfall ranges from 20 to 60 inches and occurs generally between November and March each year. The summers are characterized by advection fogs that penetrate the canyons in the coastal mountains and are intercepted by the redwood forests that thrive on fog moisture. Land in the study area is used primarily for low-density residential development, minor logging operations, and limited recreational activities.

GEOLOGY

The geology of areas including or nearby the Newell-Zayante study area has been presented in various reports since 1854, and many of these works are listed in the list of references that accompanies this report. The most recent geologic interpretation of the study area is shown in figure 2 and is taken from Brabb(1970). This mapping indicates that the rocks underlying the study area (as well as much of the central Santa Cruz Mountains) are marine clastic sediments of Tertiary age interbedded with Tertiary volcanic material. These rocks are folded and faulted, and the geologic structure trends northwestward. The structure is especially complex in the vicinity of major faults, such as in the southern part of the study area where the main structural feature is the Zayante fault (Cummings, Touring, and Brabb, 1962, p. 214).

The geologic units present in the study area are given in figure 2. Each of the geologic units is discussed briefly in table 1 according to its noteworthy features as they apply to the erodibility of the basins. A relative erodibility is assigned to each unit based on a subjective overview of erosion processes observed both in the field and on stereoscopically paired aerial photographs taken during the study period. Relative erodibility of a geologic unit refers to the potential of that unit as a source of fluvial sediment. It is a qualitative parameter that acts only as a general planning guide; to express erodibility in quantitative terms would require a detailed study that is beyond the intended scope of this project. The discussions in table 1 will serve to illustrate the conditions involved in evaluating erodibility.

LAND USE

The study area lies within a landscape which, because of its geomorphic history, offers its primary resistance to accelerated erosion by supporting a protective vegetal covering. Therefore, almost any activity by man which displaces vegetal covering on this landscape cannot avoid causing at least a temporary and local increase in the potential for accelerated erosion of the disturbed area.

Within the study area, road construction is the principal land-use activity that exposes soil and bedrock to the erosive forces of running water and gravity. Other land-use activities such as recreation, minor logging operations, and the clearing of sites for low-density, single-residence construction are generally much less disruptive to the landscape than the road construction associated with them (California Division of Soil Conservation, 1971, p. 19).

Road construction generally takes place during the summer months, and erosion of the areas disturbed during construction is initiated by fall and winter rains. Landslides, gullies, debris, fans, and other features causing damages to roads either are repaired between storms or are neglected for longer periods depending upon the necessity for use of the roads. When the roads are repaired, slide debris and other deposits on the roadways commonly are used to fill gullies and areas that were eroded or are dumped downslope from the roadways (fig. 9).

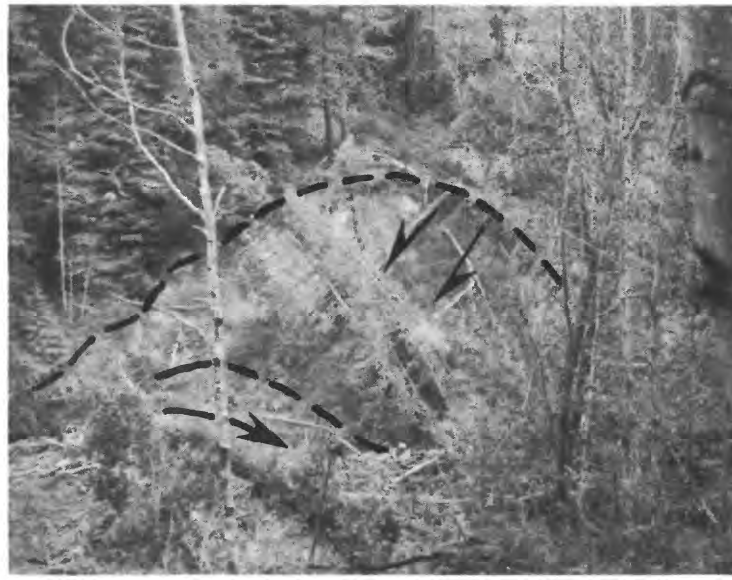
TABLE 1.--*Characteristics and relative erodibility of geologic units in the study area*

[The geologic units are shown on the map of the study area (fig. 2). References in the remarks column to the condition of the landscape are based on field and aerial photographic observations prior to March 31, 1971, unless otherwise noted, and may not reflect changes that have taken place since that time.]

Name and map symbol	Geology	General character	Percent of study area underlain by geologic unit		Relative erodibility	Remarks
			Newell Creek	Zayante Creek		
Purisima Formation (Tp)	Medium to very fine-grained sandstone and a fairly common dark-gray silty mudstone (Cummings, Touring, and Brabb, 1962, p. 197).	Massive, and poorly bedded or locally cross-bedded. Unlikely to produce landslide topography; however, minor rockslides occur in exposures.	0	7.2	Moderate	Shows no apparent signs of severe active erosion. The area underlain by the unit is small, protected by a forest canopy, and is generally unaffected by road-building or other landscape alterations. However, because the unit has a moderate erodibility, the proximity of the unit to the proposed Zayante reservoir should demand attention to erosion retardation on access roads and other potential constructions to prevent sediment-induced turbidity in the reservoir.
Santa Cruz Mudstone of Clark (1966) (Tsc)	Slightly siliceous organic mudstone (Clark, 1966, p.133)	Medium- to thick-bedded; lacks distinct fissility and will slide or slump under adverse conditions.	0	3.1	High	Exposed on slopes that will become saturated during filling of the proposed Zayante reservoir, presenting a hazard of slumping of the reservoir banks. [A small slump probably activated by lateral cutting of Zayante Creek occurs in the unit about 1,500 feet south of Camp Wasibo (fig. 3), typifying the process likely to be initiated in this area during reservoir filling.] The unit is not sufficiently extensive to be considered a major sediment source, but its proximity to the proposed reservoir demands attention to potential localized sediment problems.
Santa Margarita Sandstone (Tsm)	Moderately sorted sandstone.	Thick-bedded to massive and thickly cross-bedded.	Negligible	0	Very low	Present only as a small outcrop on the drainage basin boundary west of Loch Lomond, and presents no potential erosion problems. South of the study area, however, this unit is highly erodible.
Monterey Shale (Tm)	Mudstone, only locally sufficiently fissile to be properly termed shale. High content of organic matter and discontinuous laminae of clastic material (Clark, 1966, p. 97).	Medium- to thick-bedded irregularly laminated, and decomposes into porcelaneous debris in exposures.	5.8	1.0	Low (locally moderate)	Constitutes the foundation rock for Newell Creek Dam. The unit occurs only in the southern extremities of the study area, and forms steep, resistant slopes that are presently forested and show few signs of accelerated erosion. [A landslide in the unit on the east bank of Loch Lomond is discussed on page 27 of this report.]
Lompico Sandstone of Clark (1966) (Tlo)	Medium- to fine-grained sandstone.	Massive to thick-bedded; not prone to sliding or slumping in the study area.	1.5	0.6	Low	This unit, because of its small extent and lack of observed accelerated erosion processes in the study area should not be considered a significant contributor to fluvial sediment.
Lambert Shale (Tla)	Organic mudstone	Thin- to medium-bedded; decomposes into friable blocks and fine, easily transported particles.	3.5	9.0	Moderate (locally high)	Except in small areas in the canyons of Zayante Creek and Mountain Charlie Gulch, this unit underlies ridgetops, flats, and relatively gentle slopes. [Typical erosion of Lambert Shale in a roadcut is shown in fig. 4.]

Vaqueros Sandstone (Tvq)	Moderately sorted, very fine to medium-grained sandstone and many interbeds of mudstone (Brabb, 1960, p. 58).	Laminated to very thick-bedded; complexly fractured; decomposes into friable blocks and fine to very fine, easily transported particles.	48.4	34.1	High (locally very high)	[Typical erosion of the Vaqueros Sandstone is shown in fig. 5 and is evident in roadcuts along Zayante Road north of the axis of the San Lorenzo syncline (fig. 2). Here, considerable detrital material emanates from large, steep roadcut exposures where sheet erosion and numerous small slides occur during rainstorms.] Evidences of severe erosion of this unit are not apparent on undisturbed slopes; newly exposed areas, however, become immediately susceptible to accelerated erosion.
Zayante Sandstone of Clark (1966) (Tz)	Heterogeneous sequence of interbedded pebbly sandstone, conglomerate, and sandy siltstone (Clark, 1966, p. 45).	Thick- to very thick-bedded; may slump on steeper slopes when saturated; decomposes into coarse particles.	7.9	9.2	Moderate	Underlies areas of immediate access to both Loch Lomond and the proposed Zayante reservoir. It is thus susceptible to erosion by wave cutting and saturation of reservoir banks, and is likely to be disturbed by constructions for reservoir access and relocation of facilities displaced by the reservoirs (Brown and Caldwell, 1963, p. 156).
Mindego Basalt (Tmb)	Interstratified basaltic rocks, mudstone, sandstone, and carbonate rocks (Cummings, Touring, and Brabb, 1962, p. 189).		Negligible	0.8	Very low	The limited extent of the formation in the study area precludes consideration of this unit as a significant sediment source. A vertical exposure of the unit occurs in a large cut just west of Zayante Road about 1,500 feet southwest of Camp Wasibo.
Rices Mudstone Member of San Lorenzo Formation of Brabb (1964) (Tsr)	Mudstone and siltstone	Massive and friable; decomposes into easily transported fine sediments. Dip slopes are common in this unit.	16.4	8.0	Very high	Steep slopes underlain by this unit in the upstream reaches of the study area are subject to severe erosion when exposed in roadcuts or other excavations. [Sliding on dip slopes of this unit is shown in fig. 6.]
Twobar shale Member of San Lorenzo Formation of Brabb (1964) (Tst)	Shale	Laminated; slides and flows in many localities, particularly on dip slopes underlain by the Butano Sandstone (Brabb, 1960, p. 34-39).	3.4	2.9	Very high (locally extreme)	Severe sliding and slumping of the unit occurs in areas northwest of the study area, as well as in roadcuts in the Zayante Creek basin. Even minor alterations of the landscape underlain by this unit are likely to trigger an immediate and continuing erosional response (fig. 6).
Butano Sandstone (Tb, Tbs, Tbc)	Siltstone having insufficient fissility to be termed a shale (Clark, 1968, p. 171).	Fine-grained, thin to thick bedded; decomposes in exposures into friable blocks of many sizes. Exposures in canyons and roadcuts are commonly slumped. Dip slopes are common in the unit in the upstream reaches of Newell Creek.	13.1	24.1	Very high	Excavations in this unit in the upstream reaches of the study area expose large quantities of loose soil and fractured rock that continue to decompose and move downslope during rainstorms. The steep slopes formed in this unit, its extent, and the land-uses of the area that it underlies make it a significant contributor of fluvial sediment, especially in the Zayante Creek basin. [Figs. 7 and 8 indicate erosive processes typical in the Butano Sandstone.]

FIGURE 3.--Slump in the Santa Cruz Mudstone of Clark (1966) about 1,500 feet south of Camp Wasibo. Dashed lines show visible outline of slump as viewed eastward from Zayante Road. Double arrows show general direction of downslope movement. Single arrow indicates approximate location and direction of flow of Zayante Creek. Note displacement of trees on the slumped surface. Width of slumped area is about 80 feet. Photograph taken January 20, 1972.



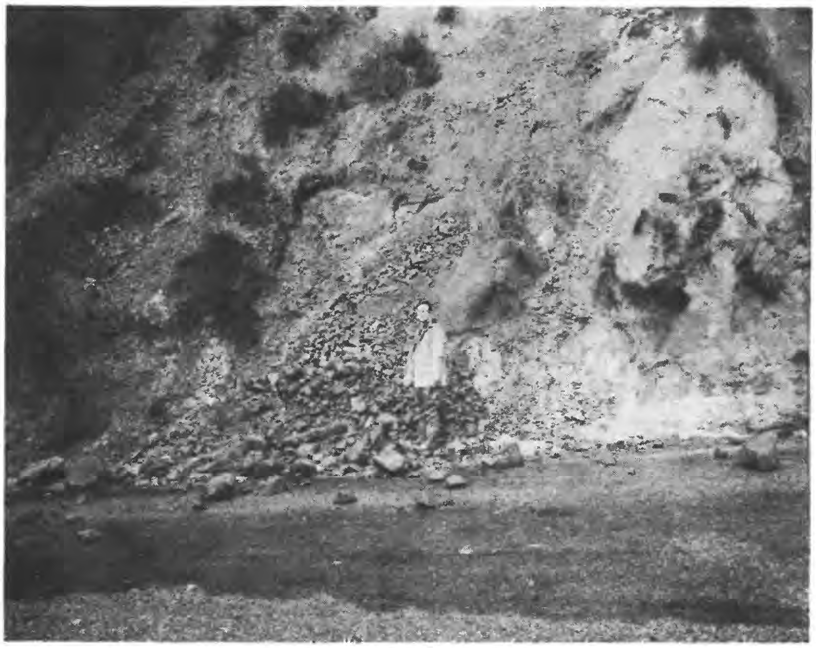
Along paved roads, erosion generally is most active during the first rainstorms following construction, although significant localized erosion may continue for an indefinite period (fig. 7). Along dirt roads, continued regrading simply exposes fresh surfaces to erosive agents (figs. 10 and 11), and erosion persists unless significant remedial measures are taken.

In the study area the quantity and quality of roads are exceedingly difficult to assess. Many small roads, especially in the deep canyons, are obscured from view in aerial photographs by the vegetation canopy. Also, roadbuilding proceeds at such a rapid pace, especially during the summer months, that only a very detailed monitoring program of frequent observations would suffice to define quantitatively the accumulative length and area of roadway construction.

It is sufficient to say the following in the absence of a detailed and continuing land-use monitoring of the study area:

1. Roadbuilding likely accounts for 80 percent or greater of the man-induced erosion in the study area (California Division of Soil Conservation, 1971, p. 19-26).

2. Roadbuilding occurs principally along ridgetops and valley bottoms in the study area, although more and more roads are being built across valley side slopes as suburban development persists.



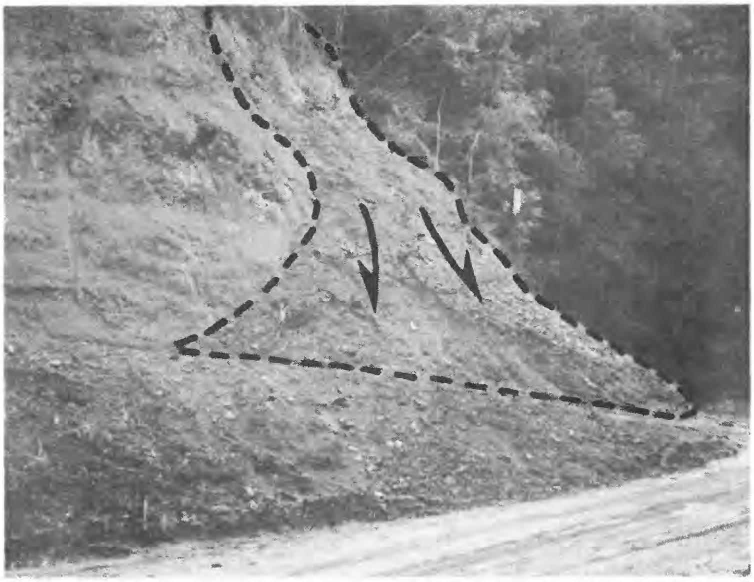
This slide occurred during a moderate rainfall in late November 1970, and is typical of slides associated with roadcuts throughout the study area.

In this closeup of the slide in the upper picture, the material directly beneath the hammer is saturated with water and is flowing slowly downslope. The blocky material can be broken and crumbled by hand.

FIGURE 4.--Disintegration of Lambert Shale in a roadcut on Zayante Road. Photographs were taken on December 2, 1970.

FIGURE 5.--Slide which occurred in late November 1970. This was one of several that emanated from the steep roadcuts in the Vaqueros Sandstone along Zayante Road.

FIGURE 6.--View of roadcut at a switchback in Zayante Road about 3,500 feet southeast of White Rock. Sliding in this vicinity occurs on dip slopes in the Rices Mudstone and Twobar Shale Members of the San Lorenzo Formation of Brabb (1964). Dashed line indicates visible uphill extent of sliding. Arrows indicate general direction of downslope movement. Photograph taken January 20, 1972.



Erosion of a roadcut in the Butano Sandstone has produced this slide which flows onto Zayante Road (foreground) and another road that trends upward to the left above Zayante Road. Arrows indicate general direction of downslope movement.

Nonsliding exposures of Butano Sandstone are a source of fine, easily transported sediment. The exposure above the two men is a continuation of the roadcut shown in the upper picture.

FIGURE 7.--Two views of exposures of Butano Sandstone about 3,500 feet east of White Rock. Scale is similar in both views. Photographs taken January 20, 1972.

FIGURE 8.--Closeup view of the upper part of slide shown in figure 7. Note the disintegration of the Butano Sandstone into friable fragments of many sizes. Dimension of large block to right of center is about 18 inches. Photograph taken January 20, 1972.

FIGURE 9.--Slide debris from roadcut in Butano Sandstone (fig. 7). Debris is piled on downslope side of roadway and moves into stream channel during runoff periods. Photograph taken January 23, 1972.

This view of a roadcut into the Vaqueros Sandstone shows the condition of the road in early October 1970. The road is within 20 feet of a stream channel which is in the brushy area to the left.

A similar view of the road in early January 1971 shows that the road is impassable owing to slumps which occurred during rainstorms in November and December 1970.

FIGURE 10.--Views westward along a narrow dirt road that intersects Zayante Road 1.25 miles south of White Rock. Note location of larger trees (arrow) and small sign in both views, and compare with figure 11.

This view of the area shown in figure 10 shows the condition of the stream channel in January 1972. Note the small pipe at left of picture and gully in center of picture. Stream channel has been obliterated, and water now flows through the pipe and on the surface of the side-cast debris.

Comparative view of roadway shown in figure 10. Material removed from roadway during 1971 was apparently dumped into stream channel at left.

FIGURE 11.--Views westward along a narrow dirt road for comparison with figure 10. Note location of trees (arrows). Photographs taken January 20, 1972.

3. Roadbuilding associated with logging in areas about 6,000 feet southwest of White Rock (fig. 2) was apparently responsible for the erosion that resulted in much of the sediment deposition in the northeast arm of Loch Lomond (Webber, W. L., and others, oral commun., 1971).

4. Land-use activities other than roadbuilding are concentrated along the ridgetops in the headwaters of Newell and Zayante Creeks and include low-density, single-residence homebuilding, and minor farming operations. These activities may be considered minimal to negligible contributors to accelerated erosion by comparison to roadbuilding. Most of the remainder of the study area, excluding Loch Lomond and its shoreline vicinity is wooded and(or) very rugged and is used principally for small logging operations or is unused, awaiting future development. [Wherever possible, parts of the study area are being purchased by the city of Santa Cruz to be managed for protection of the reservoir-water supplies (Webber, W. L., oral commun., 1971).]

5. Differences in the sediment-transport rates of Newell and Zayante Creeks (discussed subsequently in this report) are likely attributable to differences in current land-use practices in the two creek basins. In the study area, where two basins exist in very similar environments of geology, precipitation, topography, and soils, different sediment-transport rates in the two basins are induced by the artificial regulation of runoff and vegetation by various land uses. Roadbuilding is currently most intensive in the extreme northern parts of the Zayante Creek basin and in the vicinity of the Zayante Creek arm of the proposed Zayante reservoir (fig. 2) where logging preparatory to reservoir construction is taking place. However, areas of the Newell Creek basin upstream from Loch Lomond contributing to active erosion because of man's activities were small and widely scattered during the study period. This condition may be temporary and should not be construed as a long-term condition of the basin.

FLUVIAL SEDIMENT

Definition of Terms

Many terms relating to fluvial sediment are not completely standardized or may be somewhat obscure; thus, the terminology used in this report is based on the following definitions:

Fluvial sediment or *sediment* is fragmental material that originates from weathering of rocks and is transported by, suspended in, or deposited by streams.

Suspended sediment or *suspended load* is sediment that moves in suspension in water and is maintained in suspension by the upward components of turbulent currents or by colloidal suspension.

Bedload or *sediment discharged as bedload* includes both the sediment that moves along in continuous contact with the streambed (contact load) and the material that bounces along the bed in short skips or leaps (saltation load).

Sediment sample is a quantity of water-sediment mixture that is collected to determine the concentration of suspended sediment, the size distribution of suspended or deposited sediment, or the specific weight of deposited sediment.

Sediment discharge is (a) rate at which dry weight of sediment passes a section of a stream or (b) quantity of sediment, as measured by dry weight or by volume, that is discharged in a given time.

Sediment-transport curve is a curve of the relation between water discharge and sediment discharge. Usually the relation is between water discharge and suspended-sediment discharge, but it can be between water discharge and bedload discharge or between water discharge and total sediment discharge (sum of sediment discharge in suspension and as bedload).

Water discharge or *discharge* is the amount of water flowing in a channel expressed as volume per unit of time. The water contains both dissolved solids and suspended sediment.

Turbidity is the optical property of a suspension with reference to the extent to which the penetration of light is inhibited by the presence of insoluble material. In this report, turbidity generally refers to a water-sediment mixture in which the presence of suspended sediment obstructs the passage of light. Turbidity is measured in Jackson Turbidity Units (JTU) as defined by Newell (1902, p. 1-4).

The general principles of sediment-discharge measurement as well as the practical aspects of selecting sampling points and determining the frequency of sampling are discussed in several reports. A suitable reference on determination of fluvial-sediment discharge is Report 14 of the U.S. Inter-Agency Committee on Water Resources (1963). The procedure for the measurement of water discharge is described in detail by Buchanan and Somers (1969).

Erosion, Transportation, and Deposition of Sediment

Erosion, transportation, and deposition of sediment constitute a complex geomorphic system that can pose numerous problems in man's interactions with the landscape. Erosion generally refers to the wearing away of the land surface and in the study area is expressed in a variety of exposed soil and bedrock surfaces such as landslide scarps, roadcuts, and the banks and beds of stream channels and gullies. Eroded material may be transported by several agents, of which running water is usually considered the most important. Gravity, wind, and ground water may also share in the transport process, and gravity is an important transport agent in landslide areas throughout the study area. Transported sediment eventually comes to rest in depositional sites exemplified by such features as sand and gravel bars in stream channels, debris piles on roadways, and deltas at the upstream end of Loch Lomond. Obviously, erosion, transportation, and deposition are three interrelated parts of a single dynamic process. Even on the smallest scale, erosion cannot take place in the absence of a transportation mechanism; transported materials eventually must be deposited, if even for a short period of time, until they are moved again. For convenience, the dynamic process just described will be referred to hereafter in this report as the *sediment system*.

The study area lies within a landscape that offers its primary resistance to accelerated erosion by supporting a protective vegetal covering. As this covering is removed either by natural processes or by the activities of man, soil, friable colluvium, and partly disintegrated bedrock are exposed on steep slopes to annually heavy rainfall and other erosive agents. Where bedrock is exposed in stream channels, in roadcuts, on surfaces exposed by landsliding, much of it continues to disintegrate into transportable sediments. On steeper slopes, the regeneration of soil and forest cover is therefore hindered. Saturation of exposed slopes during periods of rainfall may activate further sliding and disintegration of rock, and runoff then transports loose material downslope into stream channels.

As sediment reaches the stream channels the stream must necessarily make hydraulic adjustments to accommodate the quantity and size of the sediment. An input of sediment to a given reach of channel decreases the extant capacity of the channel to carry a given flow; thus, the stream must either erode away the newly-deposited sediment, enlarge its channel by eroding the banks, or overflow the banks in order to sustain a given flow rate. In the study area, each of these processes is occurring at different points along the streams and is abetted by blockage of the channel by logs and brush (fig. 12). The responses of stream channels to these processes are changes in dimensions, shape, pattern, and gradient that ultimately affect major segments of the stream system.

FIGURE 12.--View downstream of Zayante Creek at base of switchback on Zayante Road (shown in figure 6). Dashed line outlines sediment deposited behind log jam (arrow). Sediment and other debris were deposited to a depth of about 2 feet at this location between October 1970 and January 1972. Low-water channel of the stream is visible in right center of picture. Note vegetal debris included in sediment deposit. Photograph taken January 20, 1972.

The excess sediment introduced into the stream system is eventually transferred downstream as the stream attempts to adjust its channel to a more stable form. The time required for such adjustment, however, is indeterminate for so long as a greater amount of sediment reaches the stream channel than the stream can transport under normal conditions.

In the case pertinent to this study, reservoirs are the ultimate depositional sites for fluvial sediment, and the water surface of the reservoir acts as the base level to which the stream adjusts its profile. The details of sediment deposition in Loch Lomond and the expected mechanics of sediment deposition in the proposed Zayante reservoir are discussed in the sections "Sedimentation in Loch Lomond" and "Discussion."

The eroded material that enters the stream system is transported by flowing water or deposited along the stream channel according to a complex set of variables including the available supply of sediment; the size, shape, and density of the sediment particles; the flow velocity of the stream; channel width, depth, and slope; and other physical and chemical characteristics of the water and sediment mixture (Colby, 1963). For the purposes of this report, only those factors of major importance in this study are discussed in detail. More complete explanations of the theories of sediment transport and the methods of collection and analysis of sediment data are given in Colby (1963) and Porterfield (1972).

Sediment Transport by Zayante Creek

Sediment studies began at Zayante Creek at Zayante (fig. 2) in February 1970, and daily suspended-sediment samples collected during the period February 1970 through September 1971 were analyzed to provide the data used in this report. Bedload was not studied, as the complexity of collecting and interpreting bedload data was considered beyond the scope of this project.[1] Previously collected water-discharge data for the period October 1957 through September 1971 were used to infer the nature of suspended-sediment transport prior to the collection of sediment data (table 2).

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[1]Visual observations of the stream channel at the sampling site indicated that only minor amounts of bed material were present on the bedrock channel bottom following storm periods. However, in the upstream reaches of the study area, coarse sediment commonly transported as bedload was found in depositional areas such as those described on page 18.

Table 2 shows the momentary peaks and annual mean water discharges that are used to compute the parameter Kn of Nelson (1971). Nelson (1971, p. C233) states the following:

> "The amount of sediment transported annually is dependent upon the magnitude of water discharge. In many streams, a large part of the annual suspended-sediment discharge is transported during a day in which the peak water discharge has occurred. Because of these two factors, the annual suspended-sediment discharge and Kn are related closely for many streams."

TABLE 2.--*Momentary peak and annual mean water discharge, and values of Kn for Zayante Creek at Zayante, 1958-71 water years*

Water year (ending Sept. 30 of year listed)	Momentary peak discharge (Q_{max}, cfs)	Annual mean water discharge (Q_{mean}, cfs)	[1]Kn = $\frac{Q_{max} \times Q_{mean}}{10^3}$
1958	3,700	24.5	90.65
1959	1,300	7.85	10.20
1960	880	3.85	3.39
1961	45	1.15	.05
1962	1,010	7.33	7.40
1963	2,830	18.9	53.49
1964	560	3.12	1.75
1965	1,100	11.9	13.09
1966	62	3.17	.20
1967	2,430	22.9	55.65
1968	1,240	5.28	6.55
1969	2,540	30.2	76.71
1970	1,470	15.2	22.34
1971	470	6.18	2.91

[1]Kn is expressed in terms of 10^3 rather than the 10^6 of Nelson (1971) due to the differences in magnitudes of discharges between Nelson's rivers and Zayante Creek.

In the absence of sediment data, Kn will serve as an indicator of the potential for sediment transport, assuming that no significant shift in the curvilinear relation between water discharge and suspended-sediment discharge has occurred during the period of record. Table 2 shows, therefore, that sediment discharges in the 1958, 1963, 1967, and 1969 water years were likely to have been higher than the sediment discharge computed for the 1970 water year. No significant conclusions about the magnitude of sediment discharge may be drawn from the table without additional sediment data and a definition of the long-term trend in sediment-transport characteristics. The table simply places the 1970 water-year flows in perspective with respect to sediment-transport potential. When additional suspended-sediment data become available either for Zayante Creek or a similar stream in the western Santa Cruz Mountains, the data in table 2 will be useful in estimating the long-term suspended-sediment discharge of Zayante Creek.

A sediment-transport curve for Zayante Creek at Zayante for the 1970 water year is shown in figure 13. This curve is not well defined for the full range of water discharge that might be expected to occur. For example, a momentary peak discharge of 3,700 cfs (cubic feet per second) occurred on April 2, 1958, and several discharges exceeding those measured in the 1970 water year have occurred throughout the period of water-discharge record (table 2). Therefore, the extension of the curve to incorporate the entire past water-discharge record was considered tenuous at best and was not attempted for this project. The sediment-transport curve for Zayante Creek at Zayante was extended slightly using instantaneous water-discharge and suspended-sediment discharge data for the 1970 water year. The curve and data points used to define it are shown in figure 14. Using the curve (fig. 14) and the water-discharge records for October 1969 through January 1970, suspended-sediment discharges for that period were computed and added to the record obtained by measurements of the suspended-sediment discharges for the period February 1970 through September 1970. On these bases, the suspended-sediment discharge for the 1970 water year was 50,700 tons, or about 4,570 tons per square mile of drainage area upstream from the Zayante Creek gaging station (fig. 2). About 44,000 tons or 87 percent of the annual suspended-sediment load was transported during January when about 36,000 tons were transported in the 3 days of highest flow. More than 99 percent of the annual suspended-sediment load was transported between December 19, 1969, and March 5, 1970.

Preliminary data for the 1971 water year showed that the suspended-sediment discharge was about 6,300 tons, or 570 tons per square mile. Total annual water discharge was about 2,260 cfs-day (4,480 acre-feet), and the momentary peak flow was 470 cfs. The highest daily water discharge (143 cfs) in the 1971 water year transported 2,110 tons of suspended sediment, or 33 percent of the annual total.

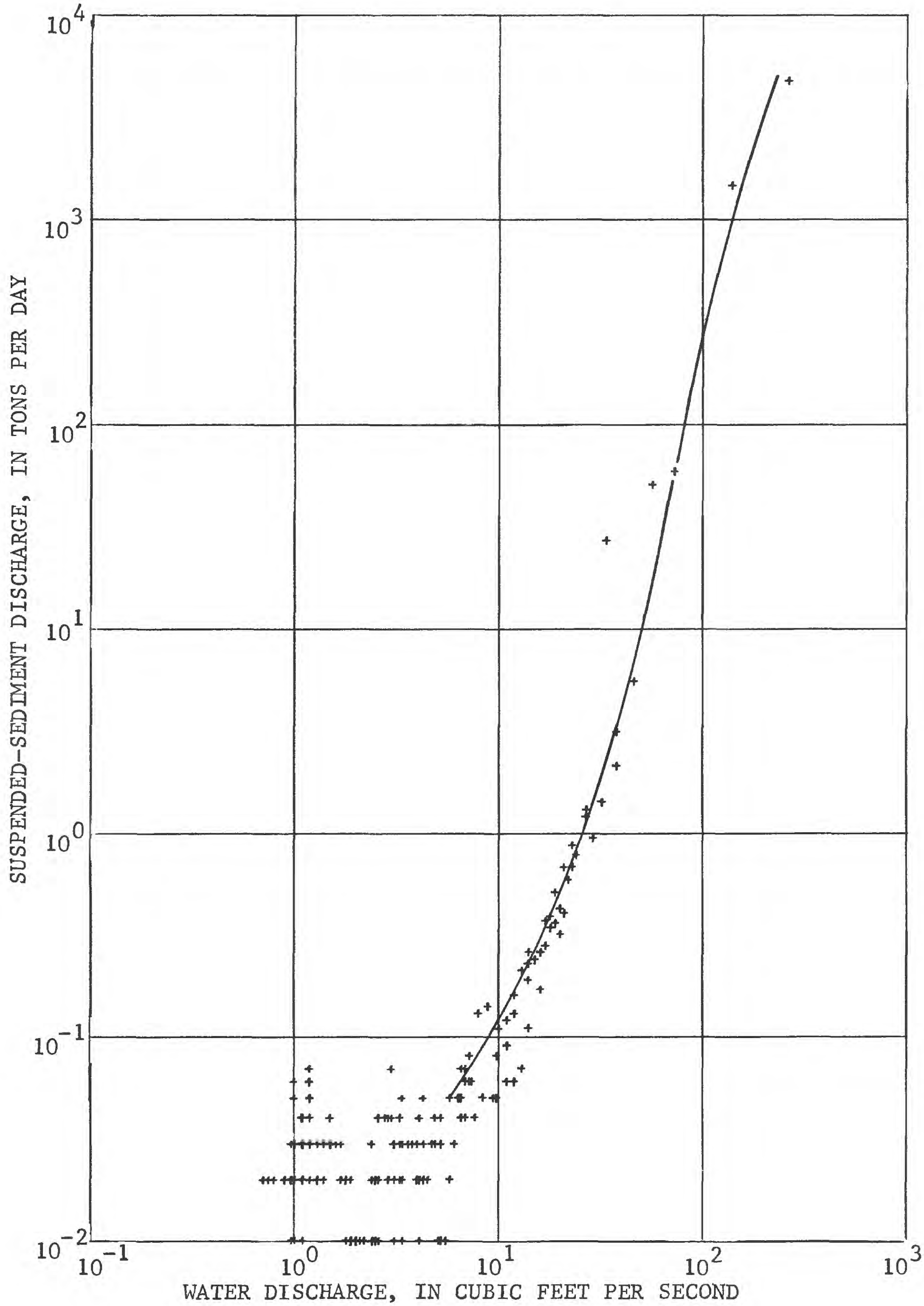

FIGURE 13.--Relation between daily average water discharge and suspended-sediment discharge for Zayante Creek at Zayante, 1970 water year.

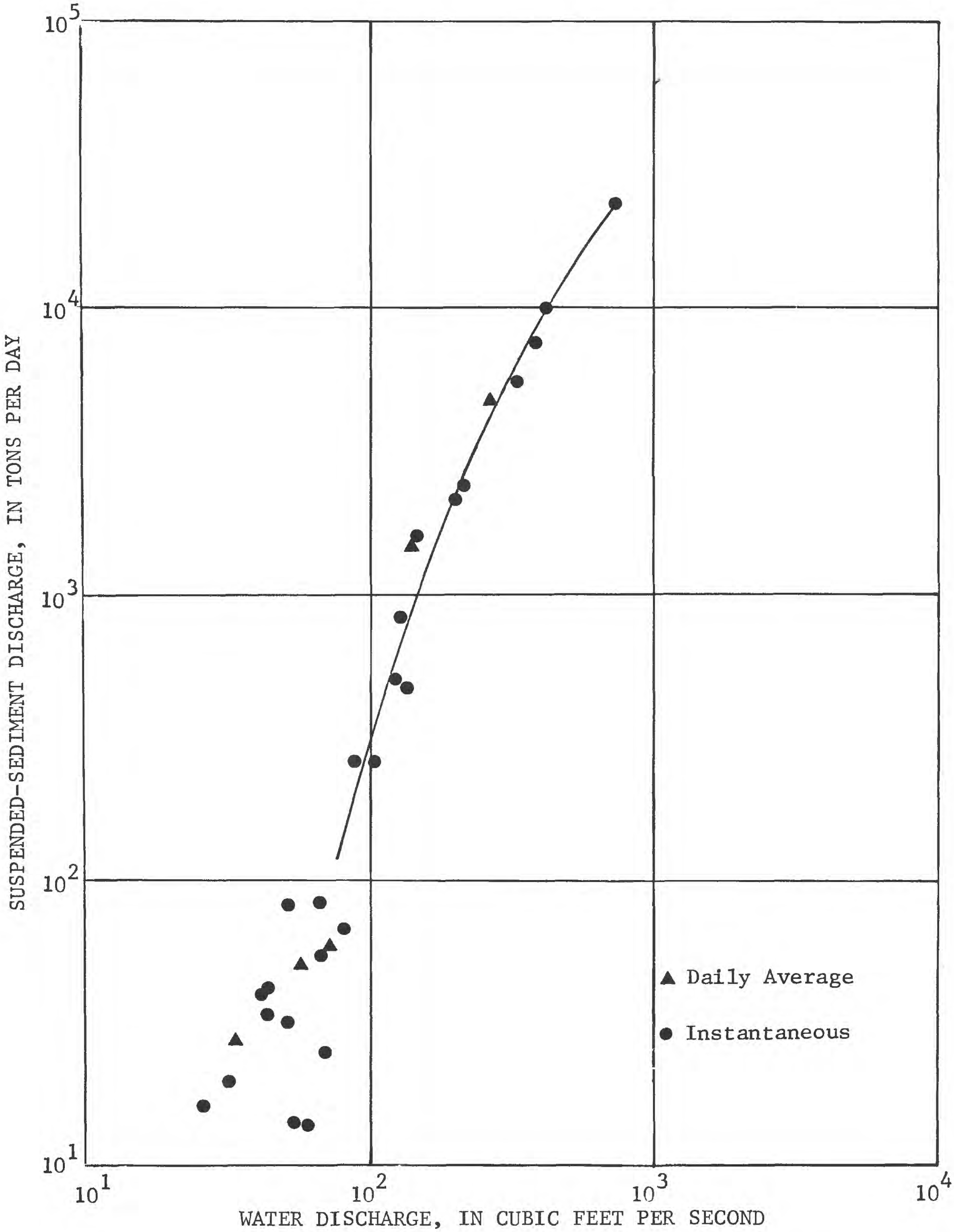

FIGURE 14.--Relation between water discharge and suspended-sediment discharge for Zayante Creek at Zayante, 1970 water year.

Sedimentation in Loch Lomond

Loch Lomond is impounded behind Newell Creek Dam (fig. 2) about 10 miles north of Santa Cruz and has been used for water supply and limited recreational activities since it was constructed in 1960. The reservoir is about 2.5 miles long and ranges in width from 400 to 1,500 feet when filled to capacity. The original capacity of the reservoir was approximately 8,600 acre-feet, and the surface area was about 180 acres at the spillway elevation of 577.5 feet above mean sea level. The reservoir trap efficiency is an estimated 95 percent based on the methods of Brune (1953).

A reservoir survey was made in September 1971 to determine the magnitude and extent of sediment deposition in Loch Lomond and to determine the characteristics of the deposited sediment. The survey included the establishment of horizontal and vertical control points that were used as a base for subsequent topographic mapping. A topographic base map (not included with this report) having a scale of 1:2,400 and a contour interval of 5 feet was compiled by Western Aerial Photos, Inc., of Redwood City, Calif. This map showed the water surface at 555 feet above mean sea level (owing to summer drawdown of the reservoir), and land-surface elevations in the range from 555 feet to 625 feet above mean sea level. Land-surface elevations above 555 feet mean sea level were mapped to an accuracy of ±1.0 foot. The topography of the reservoir sides and bottom below the water surface (555 ft) was determined from soundings at selected intervals along the cross sections shown in figures 15 and 16. The accuracy of sounding measurements ranged from 0.1 to 0.5 foot depending on the firmess of bottom sediment. Core samples of bottom sediment were collected near the lowest point on selected cross sections and were analyzed for specific weight, specific gravity, and particle-size distribution. These data are shown in table 3.

The 1971 topographic map made by Western Aerial Photos, Inc., was compared with a topographic map of the reservoir site made in 1960 by Fairchild Aerial Surveys, Inc., of Los Angeles, Calif. The 1960 map (not included in this report) was made at a scale of 1:2,400 and a contour interval of 10 feet. The 1960 thalweg profile (fig. 15) was determined by interpolating between contours on the 1960 topographic map at the superposed locations of the 1971 cross sections. Cross sections for the 1960 conditions were also drawn at the 1971 susperposed locations and were compared with the 1971 cross sections. The quantity of deposited sediment was then computed by an average end-area method (Heinemann and Dvorak, 1963, p. 845-856). The volume and weight of sediment deposited in Loch Lomond between 1960 and 1971 are given in table 4.

TABLE 3.--*Properties of sediment deposited in Loch Lomond based on samples collected in November 1971*

Cross section	Dry specific weight (pounds per cubic foot)	Specific gravity	Particle-size distribution (by percent)		
			Clay (<0.004mm)	Silt (0.004-0.062mm)	Sand (>0.062mm)
2	23.4	2.54	61.0	39.0	0.0
4	19.9	2.41	58.0	41.8	.2
6	16.6	2.66	60.0	39.4	.6
8	29.8	2.46	63.0	35.1	1.9
9	16.8	2.42	53.0	37.3	9.7
10	65.8	2.49	16.0	21.8	62.2
11	18.2	2.33	53.0	46.7	.3
13	15.4	2.37	40.0	59.4	.6
17	36.9	2.43	13.0	34.2	52.8
19	24.6	2.33	34.0	49.0	17.0
21	44.2	2.38	21.0	42.2	36.8
22	27.7	2.38	28.0	49.5	22.5
23	44.5	2.59	26.0	73.3	.7
25	40.3	--	15.0	84.1	.9
26	27.1	2.38	12.0	67.0	21.0
27	71.1	2.57	1.0	6.4	92.6
28	64.9	2.50	4.0	20.2	75.8
29	45.4	2.45	6.0	17.1	76.6
30	82.5	2.51	1.0	1.4	97.6
31	62.4	2.39	2.0	4.1	93.9
32	14.7	2.55	34.0	63.1	2.9

Because the accuracy of the 1960 map was estimated to be ±3 feet from a comparison of prominent surface features, supplementary field surveying and sediment coring were done to verify the thickness of sediment deposits. The correspondence between the 1960 and 1971 topographic maps was found to be good in areas where no sedimentation had occurred. In general, the accuracy of the volumetric data presented in table 4 is based on topographic data having an accuracy ranging from 0.1 foot where sediment deposits were small to 3 feet where sediment deposits were large.

TABLE 4.--*Volume*[1] *and weight of sediment deposited in Loch Lomond between November 1960 and November 1971*

[Cross-section numbers and specific-weight data refer to figs. 15 and 16 and table 3]

Reach (cross sections)	Distance between cross sections (feet)	Volume of deposited sediment[1] ($feet^3$)	Average dry specific weight of deposited sediment (lbs/ft^3)	Weight of deposited sediment (tons)
1-22	-	0	-	0
22-23	750	60,000	36.1	1,080
23-24	150	56,200	42.4	1,190
24-25	400	154,000	42.4	3,260
25-26	400	112,000	33.7	1,890
26-28	400	294,000	54.4	8,000
28-29	200	244,000	55.2	6,730
29-30	350	350,000	64.0	11,200
30-31	800	468,000	72.5	17,000
31-32	630	164,000	62.4	5,120
Subtotal, 1-32	---	1,902,200	----	55,500
32-33	350	42,000	14.7	310
33-end	350	42,000	14.7	310
Subtotal, 32-end	---	84,000	----	620
Totals	---	1,986,200	----	56,100

[1]Sediment volume computed by average end-area method (Heinemann and Dvorak, 1963, p. 845-856).

The results of the reservoir survey showed the following:

1. Most of the fluvial sediment deposited in the reservoir was deposited upstream from cross section 22 (table 4, fig. 15). This sediment comprised principally material of silt size or larger (table 3) and was deposited primarily in original stream channels to depths ranging from 0 to about 16 feet (fig. 15). The volume of this material was calculated for each reach between the cross sections upstream from cross section 22, and was found to be about 2,000,000 cubic feet or 56,100 tons (table 4).

2. A thin covering of very fine sediment composed principally of clay and silt (table 3, fig. 15) was deposited throughout the reservoir downstream from cross section 22 in quantities too small to be measured within the accuracy of the topographic base map. Core samples at ranges 2 through 22 (fig. 15), however, showed that in these areas, deposits ranged from 0.01 to 1 foot in thickness. These fine sediments are distributed throughout the length and depth of the reservoir immediately following storm runoff and induce turbidity that may persist for extended periods in the presence of sustained runoff. For example, turbidity levels ranging from 25 to 85 JTU at the water surface near the dam and 60 to 75 JTU at a depth of about 100 feet persisted for a 2-month period in January-March 1969 (Cross, 1971, p. 82). Normal turbidity levels were in the range of 1 to 10 JTU throughout the depths sampled by Cross for a 2-year period beginning in May 1967.

3. A significant anomaly in the bottom topography of the reservoir near the dam (fig. 15) resulted when debris from several landslides was deposited in the adjacent channel of Newell Creek on the east bank of the reservoir (fig. 2). A comparison of the 1960 and 1971 cross sections indicated that these landslides originated from areas below the spillway elevation of the reservoir (577.5 ft above mean sea level) and thus added no new sediment to the reservoir.

4. The leading edge of deltaic sediment deposition was between cross sections 27 and 28 as determined by reconnaissance in early 1971. As the reservoir was drawn down during the summer months, the base level of Newell Creek was lowered, and the stream began to erode its delta, moving previously deposited sediment farther downstream into the reservoir. It is expected that as the water surface of the reservoir rises during the winter rains more deposition will occur in the eroded areas of the delta. The newly deposited sediment subsequently will be eroded during a drawdown period, and in this manner sediment will move farther into the reservoir.

DISCUSSION

From November 1960 through November 1971 sediment deposition in Loch Lomond caused a water-storage capacity loss of at least 46 acre-feet, or about 0.5 percent of the original reservoir capacity. This figure must be considered a minimum based on (1) an estimated reservoir trap efficiency of about 95 percent of the inflowing sediment (predominantly fine sediment passes through the reservoir); and (2) the presence of a thin layer of fine sediment apparently deposited throughout the reservoir that could constitute several tens of acre-feet.[2] The 46 acre-feet of deposited sediment represents a sediment-yield rate of about 1,100 tons per year per square mile of drainage basin upstream from the reservoir arms where the major deposition occurred. This yield is comparable with sediment yields of 460 to 1,030 tons per square mile reported for rural streams in nearby Santa Clara County for 1962-69 (Ritter and Brown, 1972). Alternatively, the sediment-yield rate of the upper Zayante Creek basin was computed to be 4,570 tons per square mile for what was apparently normal runoff in the 1970 water year and 570 tons per square mile in 1971, a water year of very low runoff. These rates suggest that the area upstream from the proposed Zayante reservoir is susceptible to larger sediment yields than the area upstream from Loch Lomond, given that the land-use practices observed during the study period prevail. Currently, roadbuilding and other operations that remove vegetal covering from the landscape and result in accelerated erosion are being practiced predominantly in the Zayante Creek part of the study area. Roadbuilding is relatively minor in the area upstream from Loch Lomond. The duration of the effects of the activities contributing to accelerated erosion or the effects of infrequent high water discharge on sediment discharge in the Zayante Creek basin remain to be measured.

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[2]For example, a layer of sediment 0.5 foot thick deposited over 180 acres of reservoir bottom would constitute 90 acre-feet. The measurement of such sediment would require very detailed surveying and an extensive amount of core sampling. The cost of such a detailed survey is probably unwarranted at the present time because the loss in original water storage, thus far, is small.

The proposed Zayante reservoir is expected to have a maximum water-storage capacity of 15,200 acre-feet (Brown and Caldwell, 1963, p. 155). In a hypothetical example, therefore, a 20-percent capacity loss in 50 years would require sediment deposition at a rate of about 61 acre-feet per year. This figure represents a sediment-yield rate of about 6,900 tons per square mile per year which is equivalent to about 5 times the yield rate upstream from Loch Lomond. This sediment yield seems somewhat excessive but not unreasonable since the existing data were obtained during a short period which did not include any major floods. Thus, it is sufficient to say that the proposed Zayante reservoir probably can accommodate the sediment yield of its drainage basin for a 50-year period with a water-storage capacity loss of less than 20 percent, *given the existing conditions of the sediment system in the basin.*

It is presumed, however, that additional problems related to reservoir sedimentation may occur and should be considered in relation to the proposed Zayante reservoir. These include in the long term: (1) Channel aggradation upstream from the reservoir; (2) channel degradation of the stream system downstream from the reservoir; (3) localized landslide activity along the reservoir banks; (4) turbidity induced by the presence of suspended sediment during periods of high runoff; (5) water-quality problems related to the presence of organic matter sorbed on sediment particles; (6) water-treatment problems related to the removal of sediment from hydraulic machinery and water-distribution systems; and (7) problems related to the distribution of deposited sediment in the reservoir.

Critical to the planning for sediment-related problems are considerations of phenomena which although untested in the study area are nevertheless relevant. Sediment yield is a transient phenomenon although it is described for planning purposes in terms of an average rate correlative with streamflow. However, long-term average rates of sedimentation are often meaningless in environments that are altered by the short-term activities of man or improbable natural phenomena. Minor road-building and other construction projects tend to contribute such a disproportionate amount of sediment that the preconstruction sedimentation rate becomes insignificant by comparison, and a totally new context for sediment-yield evaluation must be established. Infrequent severe flooding may produce a sediment yield during a single storm that is considerably greater than the accumulated total yield expected for several years of moderate runoff (Brown and Ritter, 1971, p. 23-25). Thus, the possible effects of the greatest storm peaks which are expected to occur during the design life of reservoirs or other facilities affected by sedimentation should be given close attention. Also, because of the great importance of vegetation in diminishing rapid erosion in the Santa Cruz Mountains, the recurrence interval, type, and probable areal extent of destructive fires should be included in a definitive planning study.

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