EFFECTS OF LIMESTONE QUARRYING AND CEMENT-PLANT OPERATIONS ON RUNOFF AND SEDIMENT YIELDS IN THE UPPER PERMANENTE CREEK BASIN, SANTA CLARA COUNTY, CALIFORNIA

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

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MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

For additional information
write to:

District Chief
U.S. Geological Survey, WRD
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

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CONVERSION FACTORS

For readers who prefer to use International System (SI) units rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	By	To obtain SI units
acre	4,047	m^2 (square meter)
ft (foot)	0.3048	m (meter)
ft^2 (square foot)	0.09294	m^2 (square meter)
ft^3 (cubic foot)	0.02832	m^3 (cubic meter)
ft^3/s (cubic foot per second)	0.02832	m^3/s (cubic meter per second)
$(ft^3/s)/mi^2$ (cubic foot per second per square mile)	0.01093	$(m^3/s)/km^2$ (cubic meter per second per square kilometer)
inch	25.4	mm (millimeter)
in/d (inch per day)	25.4	mm/d (millimeter per day)
in/h (inch per hour)	25.4	mm/h (millimeter per hour)
lb/yd^3 (pound per cubic yard)	0.593	kg/m^3 (kilogram per cubic meter)
mile	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)
ton, short	0.9072	Mg (megagram)
ton/d (ton per day)	0.9072	Mg/d (megagram per day)
$(ton/d)/mi^2$ (ton per day per square mile)	0.3503	$(Mg/d)/km^2$ (megagram per day per square kilometer)
ton/ft (ton per foot)	2.976	Mg/m (megagram per meter)
ton/ft^3 (ton per cubic foot)	32.03	Mg/m^3 (megagram per cubic meter)
ton/mi^2 (ton per square mile)	0.3503	Mg/km^2 (megagram per square kilometer)
$(ton/yr)/mi^2$ (ton per year per square mile)	0.3503	$(Mg/a)/km^2$ (megagram per annum per square kilometer)
yd^3 (cubic yard)	0.765	m^3 (cubic meter)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by the following formula: $°F = 1.8 \times °C + 32$.

DEFINITIONS

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

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

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ABSTRACT

High sediment loads below headwater areas of the Permanente Creek drainage basin, Santa Clara County, California, have caused flood-control problems in downstream lowland areas. Measured sediment yields in Permanente Creek, which drains areas affected by limestone quarrying and cement-plant operations, were almost 15 times greater than yields from the West Fork Permanente Creek, which primarily drains parkland. Part of this large disparity in yields is the result of higher runoff per unit of drainage area in the Permanente Creek basin. Results of rainfall-runoff modeling indicate that the tendency for higher runoff from Permanente Creek results from natural differences in basin physiography. Although artificial features created by human activities seem to have had only minor effects on runoff, they apparently have had major effects on sediment availability.

Artificial features accounted for 273 acres (89 percent) of the 307 acres of active erosional landforms mapped in 1984. Increased availability of sediment in the Permanente Creek basin appears to be indicated by elevated intercepts of sediment-transport curves. A comparison of sediment-transport curves for the West Fork Permanente Creek with similar curves for the Permanente Creek basin suggests that the sediment yield from Permanente Creek is about 3.5 times higher than it would be under natural basin conditions. The increased yield apparently is due to an increase in sediment availability rather than an increase in runoff.

INTRODUCTION

The headwater area of the Permanente Creek drainage basin consists of steep terrain on the east side of the Santa Cruz Mountains in Santa Clara County, west-central California (fig. 1). About 14 percent of the uppermost headwater area is affected by operations associated with limestone quarrying and cement production (fig. 2). The main channel of Permanente Creek enters heavily populated lowland areas downstream of the headwaters. Throughout much of this lowland area Permanente Creek flows through an artificial flood-control channel constructed by the Santa Clara Valley Water District (SCVWD). The capacity of this flood-control channel, however, has been reduced in recent years by deposition of large volumes of sediment. To maintain channel capacity, the SCVWD dredged 35,620 yd^3 of sediment from the channel between 1976 and 1986. Total cost of these dredging operations was $201,676 (Randy Talley, Santa Clara Valley Water District, written commun., 1988).

Purpose and Scope

This report, which was prepared by the U.S. Geological Survey in cooperation with the Santa Clara Valley Water District, assesses the degree to which the high rate of sediment production in upper Permanente Creek basin is the result of natural processes operating on steep terrain. The report also assesses the degree to which the excavation, storage, transportation, and processing of earthen materials associated with the limestone quarry and cement plant have increased sediment loads. Data for runoff and sediment yield from areas disturbed and undisturbed by human activities were collected between the 1984 and 1987 water years. Data on potential sediment sources were collected by viewing time-sequential aerial photographs taken between 1948 and 1984. Data from disturbed and undisturbed areas were compared after considering factors that might cause natural variation in runoff and sediment supply.

Approach

To measure runoff and sediment transport from the headwater of Permanente Creek, streamflow-gaging station Permanente Creek near Monta Vista (11166575) was established downstream from the steep headwater area and upstream from the confluence with the West Fork Permanente Creek (figs. 1 and 2). To provide a measure of runoff and sediment transport from headwater areas unaffected by land use, streamflow-gaging station West Fork Permanente Creek near Monta Vista (11166578) was established (fig. 2). West Fork Permanente Creek drains mostly undeveloped land. Potential sediment sources in both the Permanente Creek and West Fork Permanente Creek basins were identified by mapping large-scale sources on time-sequential aerial photographs and by repeatedly surveying stream-channel cross sections established along the main channels in both basins. Some insight on sediment sources also was gained from limited synoptic sampling of sediment discharge during storms in the Permanente Creek basin. Processes that control runoff in the two basins were assessed by analyzing rainfall and runoff with respect to annual precipitation and basin soils, physiography, land use, and geology. The conceptual hydrologic system indicated by this analysis then was verified and quantified using the Precipitation-Runoff Modeling System (PRMS) of Leavesley and others (1983). Finally, sediment-transport curves for Permanente Creek and West Fork Permanente Creek were combined with results of the rainfall-runoff modeling to estimate the effects of land use on sediment yields in the Permanente Creek basin. Data on streamflow and sediment loads were collected during the 1985-87 water years. Precipitation data were collected at three raingages operated by the Santa Clara Valley Water District (gages 1-3, fig. 2). An additional raingage was installed in the West Fork basin in December 1986 (gage 4, fig. 2).

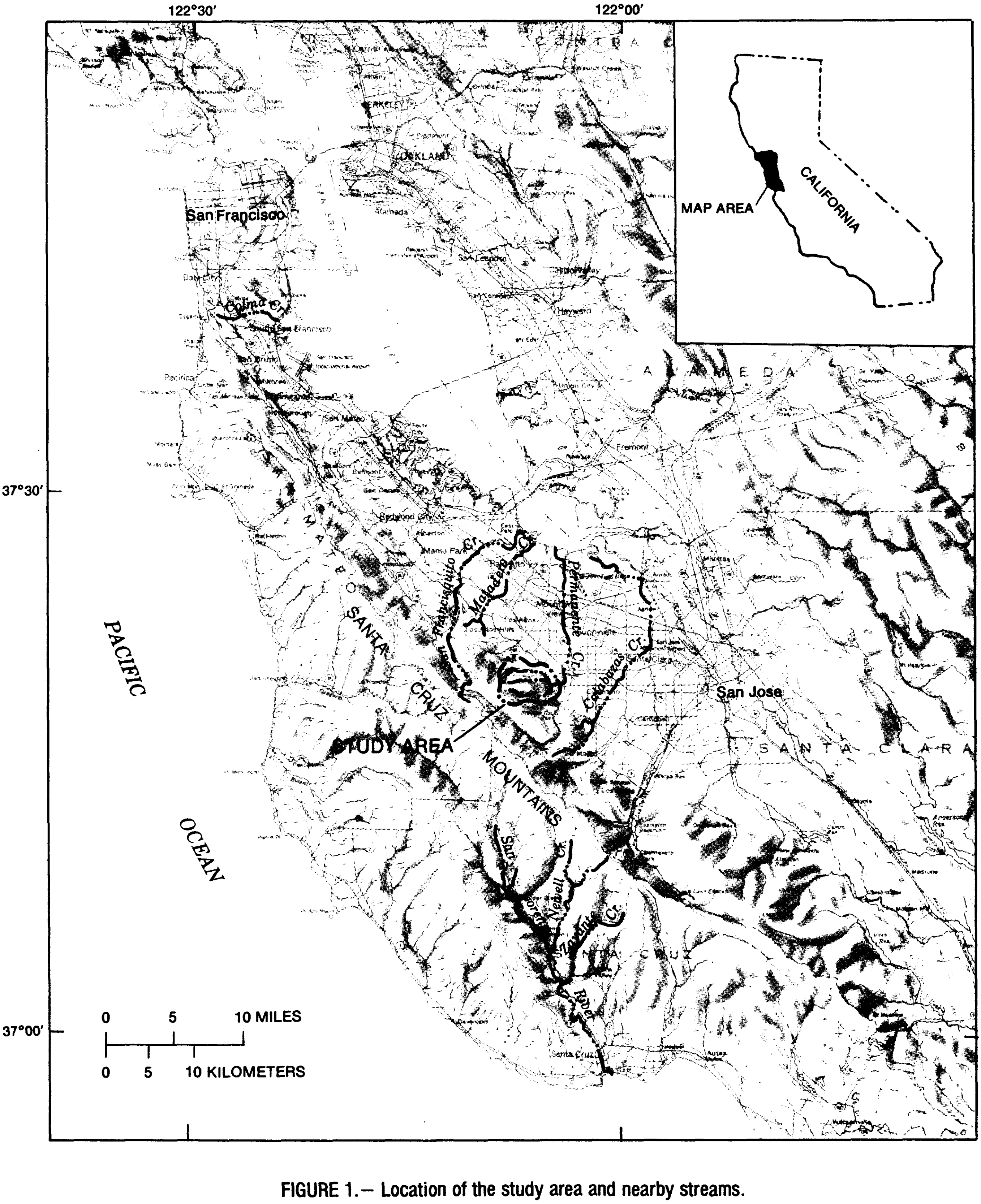

FIGURE 1.— Location of the study area and nearby streams.

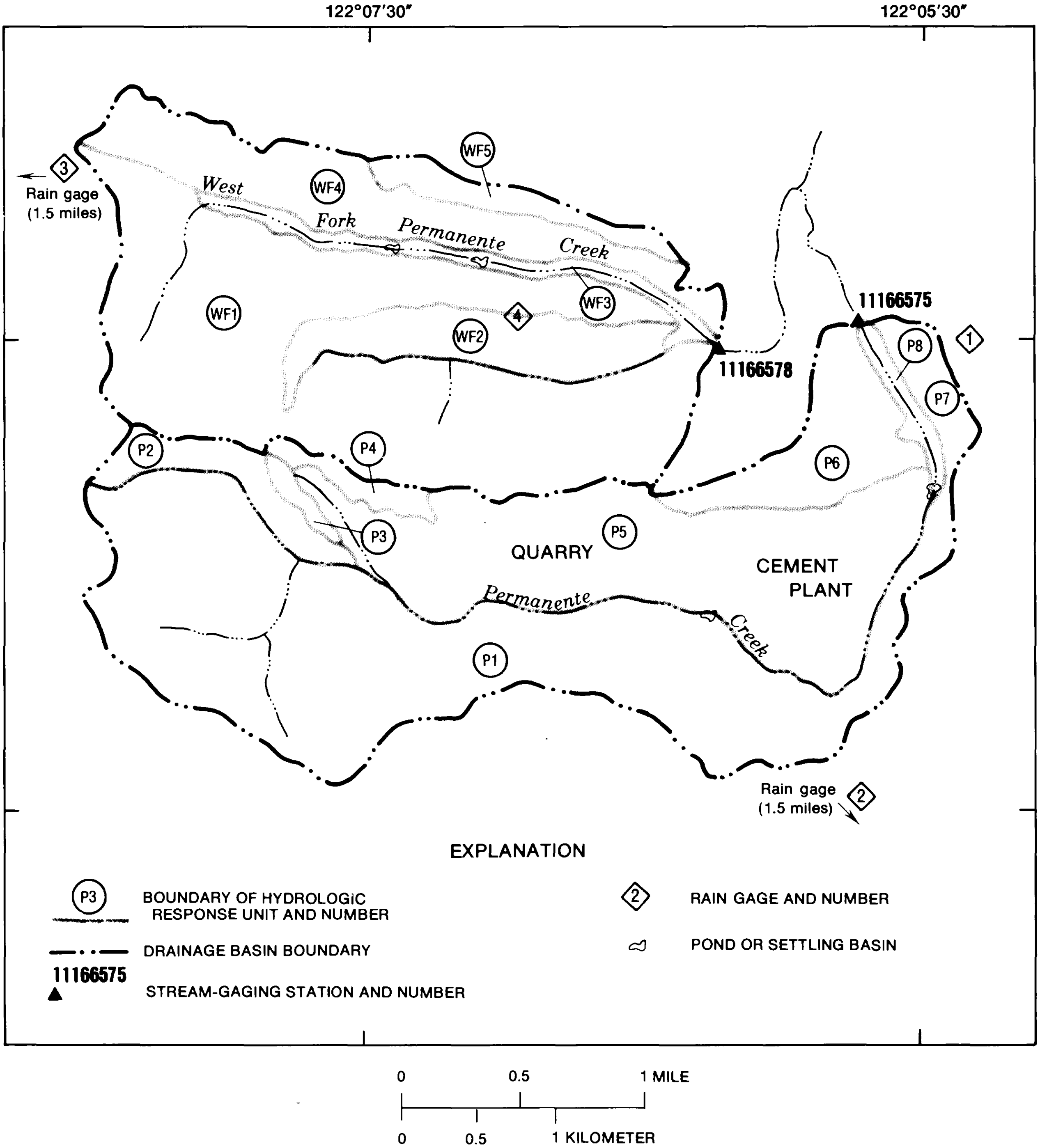

FIGURE 2.— Location of stream-gaging stations, rain gages, hydrologic response units, ponds, and settling basins in the Permanente Creek and West Fork Permanente Creek basins.

Description of the Study Area

The Permanente Creek basin lies about 40 miles south of San Francisco in central California (fig. 1). Permanente Creek descends on the east side of the Santa Cruz Mountains and empties into San Francisco Bay.

The climate of the southern San Francisco Bay region is Mediterranean and has mild, wet winters and warm, dry summers. Mean annual precipitation is 25 inches in the basin upstream from station 11166575 and 24 inches in the basin upstream from station 11166578 (Bradberry and Associates, 1963). Precipitation distribution is strongly controlled by topography; rainfall is greatest on high ridges along the west side of the basin and decreases toward the east (Bradberry and Associates, 1963). Almost all precipitation falls as rain between October and April.

The drainage basin upstream from station 11166575 has an area of 3.86 mi^2 (2,470 acres). Altitude ranges from 400 to 2,800 feet; the average is 1,400 feet. The drainage basin upstream from station 11166578 has an area of 2.98 mi^2 (1,907 acres); altitude ranges from 400 to 2,280 feet, and the average is 1,050 feet. Both basins are oriented east-west, and slopes are oriented predominantly north and south. The average land surface slope is 47 percent upstream from station 11166575 and 45 percent upstream from station 11166578.

Bedrock of the Permanente Creek and West Fork Permanente Creek basins consists largely of Jurassic and Cretaceous rocks of the Franciscan Complex (Dibblee, 1966; Rogers and Armstrong, 1973). Rocks of the Franciscan Complex underlie 84 percent of the Permanente Creek basin and 97 percent of the West Fork basin. This complex includes massive, closely fractured sandstone with interbedded shale; undifferentiated hard massive and fragmented volcanic rock (greenstone); limestone with interbedded chert, diabase, and gabbro; and serpentinite (Rogers and Armstrong, 1973). The limestone body in the Permanente Creek basin is the largest within the Franciscan Complex of the California Coast Ranges (Rogers and Armstrong, 1973). In the eastern part of the Permanente Creek basin, the Franciscan rocks are unconformably overlain by the Tertiary Monterey Shale and Tertiary and Quaternary Santa Clara Formation (Dibblee, 1966). Monterey Shale underlies 1 percent of the Permanente Creek basin, and rocks of the Santa Clara Formation underlie 8 percent. Monterey Shale and Santa Clara Formation rocks crop out primarily in the downstream one-quarter of the basin. Quaternary alluvium underlies 7 percent of the Permanente Creek basin and 3 percent of the West Fork basin. In the Permanente Creek basin, this alluvium crops out primarily along the lower mile of channel, below most of the steep terrain in the basin. In the West Fork basin, alluvium crops out along much of the main channel, well into the steep terrain.

Previous work has indicated that a variety of geomorphic processes may be active in both study basins. Landslides and surficial deposits were mapped by Rogers and Armstrong (1973), who reported that alluvium and colluvium occur only in narrow fingers along stream courses. Erosional landforms in the study area mapped by Julie Galton (U.S. Geological Survey, written commun., 1985) include several types of active and inactive landslides, gullies, rills, unstable streambanks, bare ground and slopes, impervious surfaces, spoils and storage piles, and roads.

The study area includes nine soil series mapped by the U.S. Soil Conservation Service (1968). Soil textures range from clays to stony loams. Clays underlie 2 percent of the Permanente Creek basin; clay loams, 72 percent; loams, 4 percent; and sandy, gravelly, or stony loams, 22 percent.

Vegetation in the study area consists of annual grasses, chaparral, and evergreen-broadleaf forest (primarily oak, madrone, and bay laurel). Aspect exerts a dominant control on distribution of vegetation types: swales and north-facing slopes are commonly forested, whereas south-facing slopes are chaparral covered. Grassland is found mainly at lower altitudes along the eastern boundary of the study area.

Land Use

About 15 percent (373 acres) of the Permanente Creek basin upstream from station 11166575 is affected directly by limestone-quarrying and cement-production operations. Quarry operations began in 1900 but were minor until 1939, when large amounts of cement were produced for construction of Shasta Dam (Rogers and Armstrong, 1973). As a result of quarry and cement-plant operations, about 6 percent of the area upstream from station 11166575 now consists of impervious surfaces such as roads, parking lots, and buildings (fig. 3). The main quarry pit presently is excavated to an altitude lower than the bed of the stream nearby, and seepage from the stream may be locally directed toward the pit. Water pumped from the pit is used on site and is not discharged directly to the stream channel. About a hundred acres of land drain directly into the quarry. There is a small settling pond 0.5 mile upstream from this stream-gaging station. The pond was constructed to trap sediment below the cement plant. The capacity of this settling pond has not been measured, however, 2,500 yd^3 of sediment were removed during a single cleaning operation in July 1985 (Stan Wolfe, Santa Clara Valley Water District, written commun., 1985).

Most of the Permanente Creek basin that is undisturbed by quarrying and related activities is undeveloped. A small part of the headwater area and the area immediately upstream of station 11166575 are used as wildland parks. A cemetery is adjacent to the channel between the cement plant and the gaging station. About 14 acres (0.7 percent) of land in the West Fork Permanente Creek basin are covered by low-density residential housing. The rest of the basin is undeveloped.

RUNOFF

Measured Runoff

Runoff from both study basins was measured at gaging stations 11166575 and 11166578 using standard practices of the U.S. Geological Survey (Rantz, 1982). Because of the Mediterranean climate, streamflow in Permanente Creek generally rises in late autumn or early winter and then recedes throughout a long base-flow period during spring and summer. Streamflow in West Fork Permanente Creek does not begin until middle or late winter and recedes throughout a long base-flow period during the spring and summer, after which zero flow is recorded for varying lengths of time prior to the beginning of the next rainy season. The West Fork did not flow during the dry 1987 water year; no streamflow was recorded at the Permanente Creek gage after June 1987.

A wide range of annual streamflow volumes and peak water discharges were recorded during the 3-year study period. Complete records of daily streamflow, annual peak streamflow, and total annual streamflow at stations 11166575 and 11166578 have been published for the 1985-87 water years by the U.S. Geological Survey (Anderson, Markham, Shelton, Trujillo, and Grillo, 1987, 1988; Anderson, Markham, Shelton, and Trujillo, 1988). Total runoff, mean daily peak flow, and instantaneous peak flow recorded at both stations for each of the 3 years of study are shown in table 1. February through March 1986 was an exceptionally wet period. An average of 20 inches of rain fell at three raingages operated by the Santa Clara Valley Water District between February 12 and March 17, 1986.

0 0.5 MILE

0 0.5 KILOMETER

EXPLANATION

▲ 11166578 GAGING STATION AND NUMBER

FIGURE 3. – Stereo pair of 1980 aerial photographs showing quarry, cement plant, and related land disturbances in the Permanente Creek basin.

TABLE 1.--*Summary of measured streamflow from the Permanente Creek and West Fork Permanente Creek basins*

[ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile]

Water year	Total runoff (inches)	Mean daily peak flow (ft^3/s)	Mean daily peak flow per unit area [$(ft^3/s)/mi^2$]	Instantaneous peak flow (ft^3/s)	Instantaneous peak flow per unit area [$(ft^3/s)/mi^2$]
Permanente Creek near Monta Vista (11166575)					
1985	3.81	11.0	2.8	51	13.2
1986	17.0	175	45	571	148
1987	1.44	9.2	2.4	34	8.8
West Fork Permanente Creek near Monta Vista (11166578)					
1985	0.65	1.10	0.4	2.2	0.7
1986	10.6	70.0	23	140	47
1987			no flow		

The maximum 24-hour rainfall recorded during this period was 4.5 inches. The instantaneous peak flow recorded on nearby Matadero Creek (fig. 1), which has a 34-year streamflow record, had a recurrence interval of 10 years. This recurrence interval estimate was derived using procedures outlined by the U.S. Interagency Advisory Committee on Water Data (1982).

Runoff Processes

Before effects of human activities on runoff can be assessed, it is important to understand natural runoff-generating processes. It is generally recognized that ground-water flow from deep subsurface flow systems sustains streamflow between periods of storm runoff (Freeze, 1974). Likewise, it is generally recognized that there are three basic mechanisms by which runoff is generated during storms (See Freeze, 1974). First, surface runoff can occur if rainfall intensities exceed the rate at which rainfall can infiltrate into the soil. This mechanism, commonly referred to as Hortonian overland flow, is thought to occur primarily in desert or semiarid environments where the soil surface is not protected by vegetation and where there is a lack of organic material in the soil. Second, runoff occurs when rain falls on soils that are adjacent to stream channels and that have become saturated by rising water tables. The size and location of these "variable source areas" are controlled by the amount and intensity of precipitation as well as by hillslope topography and subsurface hydrology. Third, runoff is delivered by subsurface flow (terminology from Freeze, 1974) that either enters a permanent stream channel or enters an expanding network of saturated valley bottoms or intermittent channels.

Both the Permanente Creek and West Fork Permanente Creek basins are deeply incised and have narrow valley bottoms, steep slopes, and soils with infiltration rates much higher than commonly encountered precipitation intensities. For the most part, such conditions preclude Hortonian overland flow as a dominant runoff mechanism. Most runoff probably comes either from variable saturated areas or from subsurface flow that enters stream channels or expanding variable source areas (See Hewlett, 1961; Hewlett and Hibbert, 1967; Freeze, 1974, p. 632; and Dunne, 1983, p. 29).

As table 1 indicates, total runoff and peak flows were higher in Permanente Creek than in West Branch Permanente Creek. This difference in flow results either from natural differences in the two basins that affect runoff processes or from effects of human activities on runoff. Because the two basins are close to one another and underlain by similar soils and geology, many possible causes of this difference can be eliminated. Rainfall in the two basins, for example, is similar. Bradberry and Associates (1963) indicated that mean annual precipitation is 25 inches in the Permanente Creek basin and 24 inches in the West Fork basin. Geology is also fairly similar in the two basins, but there are some differences that might account for the more seasonal nature of flow in the West Fork.

The intermittent flow in the West Fork channel probably results from the high proportion of alluvium underlying the channel, considerably more than that underlying the main channel of Permanente Creek. Mapping of surficial geology by Rogers and Armstrong (1973) indicates that 93 percent of the length of the West Fork channel is underlain by Quaternary alluvium. Only 26 percent of the length of Permanente Creek is underlain by alluvium. The alluvium along the West Fork channel apparently has a large storage capacity for water before the ground-water level rises above the channel bed. In contrast, the less permeable bedrock that crops out along many reaches of Permanente Creek allows water stored in upstream alluvium to enter the channel.

The large amount of alluvium along valley bottoms in the West Fork channel may also be responsible for lower unit peak flows (table 1) in the West Fork. This alluvium probably acts as a large, porous reservoir for direct precipitation and subsurface flow from hillslopes. The alluvium would, therefore, reduce the size of variable-source areas adjacent to the main channel and slow the flow of subsurface water into the main channel.

Higher unit peak flows in Permanente Creek also may have resulted from human activities in the Permanente Creek basin. Recent work by Harr and others (1975), Harr (1976), and Ziemer (1981), however, indicates that human activities in Permanente Creek might not have a major effect on runoff, particularly during wet periods. Harr and others (1975) and Harr (1976) found that roads and other impervious areas associated with timber harvesting had little effect on runoff until more than 12 percent of the basin was occupied by impervious surfaces. Likewise, Ziemer (1981) found no effect of roads on large peak streamflows when roads occupied less that 5 percent of the south fork of Casper Creek in west-central California. These previous studies indicate that land use in the Permanente Creek basin probably has not had major effects on runoff, because only 6 percent of the basin upstream from station 11166575 is occupied by roads or other impervious surfaces.

Rainfall-Runoff Modeling

The Precipitation-Runoff Model (PRM) was used to evaluate variations between hydrologic conditions in the Permanente Creek basin upstream from station 11166575 and station 11166578 and to make inferences about the effects of land use on runoff in the Permanente Creek basin.

Precipitation-Runoff Modeling System

The Precipitation-Runoff Modeling System (PRMS) is a distributed-parameter model that can simulate both daily-flow (daily mode) and storm-runoff hydrographs (storm mode). PRMS requires that the drainage basin be partitioned into units that are homogeneous with respect to slope, aspect, vegetation type, soil type, and precipitation distribution. Each of these units is considered homogeneous in its hydrologic response and is called a hydrologic-response unit (HRU). This partitioning allows discrimination of effects of different land uses on a drainage basin's hydrologic response. Basin partitioning is further described by Leavesley (1973) and Leavesley and others (1983).

The conceptual hydrologic system used in PRMS is shown in figure 4. Precipitation in the Permanente Creek basin comes in the form of rain. In PRMS, rainfall, after being reduced by vegetation interception, is routed into a series of four reservoirs whose outputs are logged and combined to produce the total basin response. Daily soil moisture is accounted for in the soil profile,

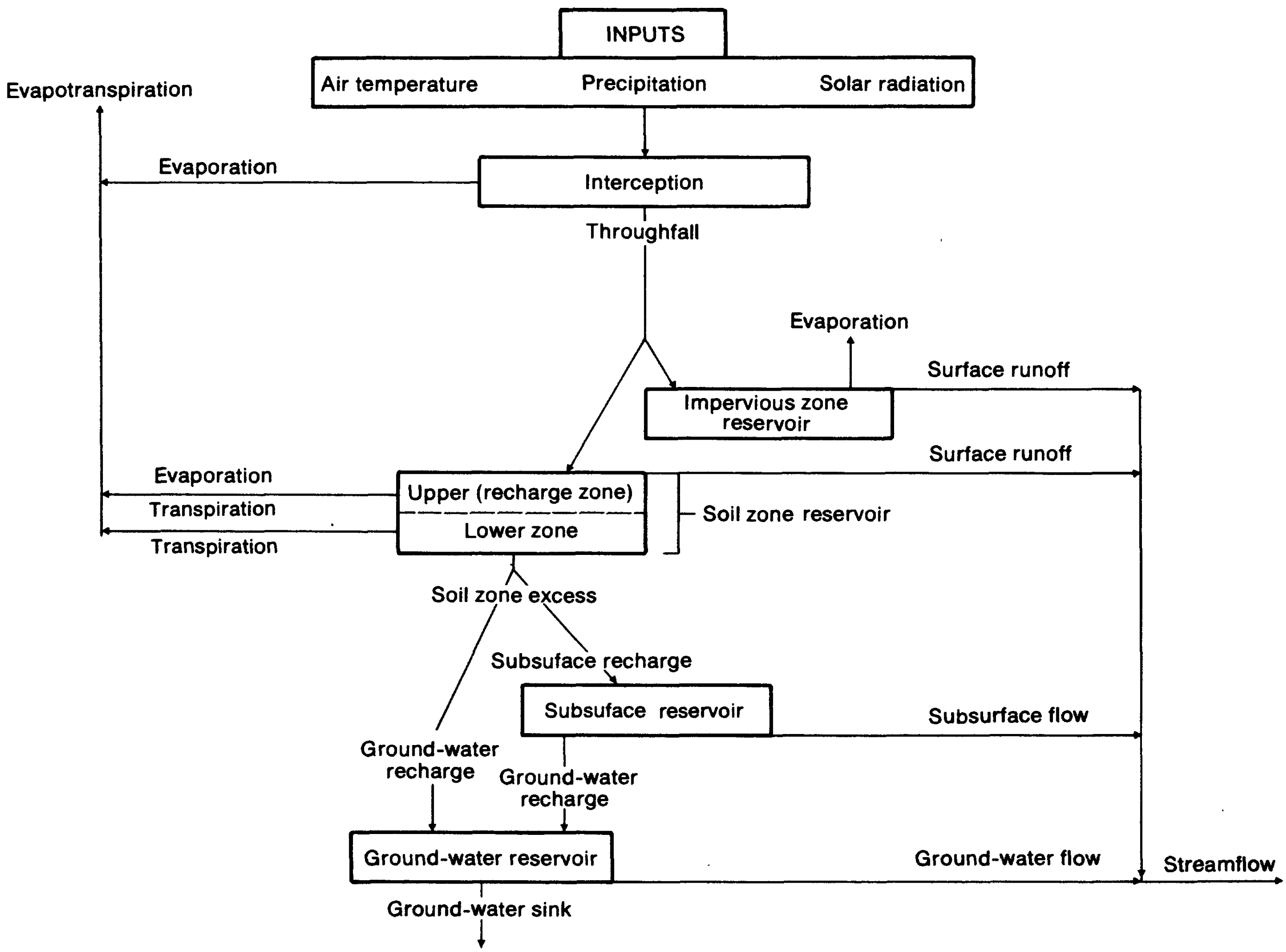

FIGURE 4.— Conceptual hydrologic system used in the Precipitation Runoff Modeling System (modified from Leavesley and others, 1983).

the depth of which equals the average rooting depth of the dominant vegetation in each HRU. The soil profile is divided into an upper (recharge) and lower zone. Rainfall infiltrates from the upper to the lower zone. The upper soil zone loses water by evaporation and transpiration, whereas the lower zone loses only by transpiration. Evapotranspiration is driven by average daily temperature and solar radiation. When the water-holding capacity of the lower zone is exceeded, the excess is added to a subsurface reservoir. The subsurface reservoir contains soil water that percolates to a ground-water reservoir or that moves downslope to some point of discharge above the water table. A decay function determines seepage from the subsurface reservoir to the ground-water reservoir. User-defined functions control flow from the subsurface and ground-water reservoirs to the stream. Leavesley and others (1983) used the term "subsurface flow" to designate the relatively rapid movement of water from the unsaturated zone to the stream channel.

In daily mode, PRMS simulates surface runoff using the contributing-area concept (Dickinson and Whiteley, 1970; Hewlett and Nutter, 1970). PRMS provides the capability of simulating surface runoff as either a linear or nonlinear function of antecedent soil moisture and rainfall amount. The nonlinear scheme was used in the Permanente Creek basin. Use of the nonlinear scheme was suggested by G.H. Leavesley (U.S. Geological Survey, oral commun., 1987), who has found that it better describes the physical situation in steep terrain. The nonlinear scheme uses a moisture index (SMIDX) for estimating contributing area (CAP). CAP is computed as follows:

$$CAP = SCN \times 10^{(SC1 \times SMIDX)} \qquad (1)$$

where SCN and SC1 are coefficients, and SMIDX is the sum of the current available water in the soil zone plus half the daily net precipitation.

In storm mode, PRMS simulates surface runoff by calculating the amount of rainfall in excess of that which infiltrates into the soil. Point infiltration is calculated using a variation of the Green and Ampt (1911) infiltration equation. Point-infiltration capacity at a given time (FR) is computed as follows:

$$FR = KSAT \times (1.0 + \frac{PS}{SMS}). \qquad (2)$$

where

KSAT is vertical hydraulic conductivity of the transmission zone, in inches per hour;
PS is effective value of the product of capillary drive and moisture deficit, in inches; and
SMS is the value of accumulated infiltration, in inches, at a given time.

Rainfall excess over an entire area is computed assuming that net infiltration varies linearly from zero to FR. Rainfall excess is simply net rainfall minus net infiltration. Rainfall excess from effective impervious surfaces is determined using rainfall as inflow. All rainfall excess enters the stream as surface runoff. The amount of effective impervious surface in a given HRU was initially estimated using the amount of impervious surfaces mapped on 1984 aerial photographs of the basin. These values were modified following initial model runs. The amount of effective impervious area in a given HRU was always less than the amount of impervious area mapped on aerial photographs. Differences between these two sets of values probably result from (1) surface detention storage and (2) runoff from some impervious surfaces not discharging directly into a through-going stream. Rainfall early in the rainy season was particularly useful in estimating effective impervious area because runoff from other sources, such as subsurface and ground water, was low during those times.

Data Input

The Permanente Creek drainage basin was partitioned into eight HRU's, and the West Fork Permanente Creek drainage basin was partitioned into five HRU's (fig. 2). Major characteristics of each HRU are shown in table 2. Areas of the Permanente Creek basin that drain into the quarry were not included in the modeling. Average characteristics of soils in all HRU's were determined using information from soil surveys for the basin (U.S. Soil Conservation Service, 1968). Physiographic characteristics for all HRU's were measured from 1:24,000-scale topographic maps. PSP and RGF, which represent the combined effect of moisture deficit and capillary potential, were estimated from initial model runs. Values of PSP and RGF (defined in table 2) are used to calculate PS. Seven of the most important coefficients used to describe ground-water or subsurface flow in the basins as a whole are shown in table 3. Initial values of these seven coefficients were estimated using initial model runs. The value of the coefficient used to route ground water to streamflow (RCB) was estimated using optimization procedures outlined by Leavesley and others (1983).

Rainfall between October 1984 and December 1986 in the vicinity of Permanente Creek basin was measured at the three recording raingages operated by the Santa Clara Valley Water District (fig. 2, gages 1-3). These gages record every time rainfall exceeds 0.10 inch. A fourth recording raingage, which records a continuous trace (fig. 2, gage 4) was installed in a study basin in December 1986.

Model Calibration

The 3-year study period, coupled with the dry conditions in 1985 and 1987, provided few storms on which PRMS could be calibrated. The entire 3-year period therefore was used for model calibration, with the result that the calibrated model could not be checked against an independent data set. Model calibration was first done for the Permanente Creek basin. PRMS was used in storm mode for seven storms, which totaled 31 days. Flow was present in the West Fork during only four of those storm periods. Except for those characteristics that were based on physical data, characteristics determined by calibration on Permanente Creek data were transferred to the West Fork. Changes were made in characteristics that were not based on physical data only when necessary to produce fits to measured flow in the West Fork. Changes were made in values of RCB, the coefficient used to route ground water to streamflow, RSEP, the coefficient used to route subsurface flow to the ground-water reservoir, and GSNK, the seepage rate from the ground-water reservoir to the ground-water sink.

It was not possible to use PRMS in continuous mode for the West Fork between 1985 and 1986 because the creek did not flow between July 12, 1985, and February 14, 1986. PRMS cannot handle intermittent flow like that in the West Fork because, in the model design, once water leaves the soil reservoir, it cannot be retained in either the subsurface or ground-water reservoirs without some water being discharged to the stream. Flow began in 1985 and 1986 after an average of 10.0 and 10.5 inches of rain, respectively, fell in the West Fork basin. Because this is more water than could be retained in the soil reservoir, even after accounting for evapotranspiration, PRMS would have predicted flow before any actually occurred. PRMS was used for the West Fork only for periods when flow was recorded in the channel. Soil moisture conditions at the onset of streamflow, which can be user specified, were assumed to be high.

TABLE 2.--*Major characteristics used in describing hydrologic response units*

[Capitalized abbreviations are those used by Leavesley and others (1983). Hydrologic response unit locations shown in figure 2. in/d, inches per day; in/h, inches per hour]

Hydrologic response unit	Area (acres)	Ground slope (percent) [SLP]	Coefficients in contributing area relation		Effective impervious area (percent) [IMPERV]	Dominant vegetation cover [ICOV]	Vegetation cover density (percent)	
			SC1	SCN			Summer [COVDNS]	Winter [COVDNW]
Permanente Creek near Monta Vista (11166575)								
P1	1,346	0.54	0.01	1.0	0.00	trees	90	80
P2	103	.61	.01	1.0	.00	shrubs	90	80
P3	18	.36	.01	1.0	.00	trees	90	80
P4	50	.57	.01	1.0	.00	shrubs	90	80
P5	804	.44	.01	1.0	.15	bare	5	5
P6	238	.35	.01	1.0	.00	trees	90	80
P7	27	.02	.01	1.0	.01	grass	70	60
P8	92	.17	.01	1.0	.01	grass	70	60
West Fork Permanente Creek near Monta Vista (11166578)								
WF1	482	0.53	0.01	1.0	0.01	trees	90	80
WF2	202	.41	.01	1.0	.00	grass	90	80
WF3	692	.47	.01	1.0	.00	grass	90	80
WF4	243	.31	.01	1.0	.00	shrubs	90	80
WF5	285	.41	.01	1.0	.00	shrubs	90	80

Hydrologic response unit	Interception storage capacity (inches)		Storage capacity (inches)		Hydraulic conductivity of soil zone (in/h) [KSAT]	Seepage rate, soil zone to ground water (in/d) [SEP]	PSP[1]	RGF[2]
	Summer [RNSTS]	Winter [RNSTW]	In upper soil zone [REMX]	Of soil [SMAX]				
Permanente Creek near Monta Vista (11166575)								
P1	0.1	0.05	0.5	5.7	1.29	0.1	2.0	9.0
P2	.1	.05	.5	5.8	1.32	.1	2.0	9.0
P3	.1	.05	.5	5.8	1.84	.1	2.0	9.0
P4	.1	.05	.5	5.8	1.32	.1	2.0	9.0
P5	.0	.0	.5	5.0	1.32	.1	2.0	9.0
P6	.1	.05	.5	6.0	1.26	.1	2.0	9.0
P7	.05	.02	.5	9.0	.42	.1	2.0	9.0
P8	.05	.02	.5	6.8	1.07	.1	2.0	9.0
West Fork Permanente Creek near Monta Vista (11166578)								
WF1	0.1	0.05	0.5	5.6	1.31	0.02	2.0	9.0
WF2	.1	.05	.5	5.8	1.32	.02	2.0	9.0
WF3	.1	.05	.5	6.9	1.02	.02	2.0	9.0
WF4	.1	.05	.5	5.8	1.32	.02	2.0	9.0
WF5	.1	.05	.5	5.8	1.32	.02	2.0	9.0

[1]Parameter in Green and Ampt (1911) equation. Product of matric suction at wetting front and difference between volumetric soil moisture at effective saturation and field capacity.

[2]Parameter in Green and Ampt (1911) equation. Product of matric suction at wetting front and difference between volumetric soil moisture at effective saturation and permanent wilting point to PSP.

TABLE 3.--*Selected coefficients used in the Precipitation-Runoff Modeling System simulation of runoff from the Permanente Creek and West Fork Permanente Creek basins*

[Capitalized abbreviations are those used by Leavesley and others, 1983]

Coefficient for seepage rate from ground-water reservoir to ground-water sink	Coefficient for routing ground water to streamflow	Coefficients for routing subsurface flow to streamflow[1]		Coefficients for routing subsurface flow to the ground-water reservoir[2]		
(GSNK)	(RCB)	RCF	RCP	RSEP	REXP	RESMX
Permanente Creek near Monta Vista (11166575)						
0.30	0.015	0.04	0.10	0.30	0.50	1.00
West Fork Permanente Creek near Monta Vista (11166578)						
0.08	0.015	0.02	0.02	0.10	0.50	1.00

[1]Coefficients used in the equation:

$$\frac{d(RES)}{dt} = INFLOW-(RCF\times RES)-(RCP\times RES^2)$$

where RES is storage volume in the subsurface reservoir and INFLOW is the rate of inflow to the subsurface reservoir.

[2]Coefficients used in the equation:

$$GAD = RSEP\times\left(\frac{RES}{RESMX}\right)^{REXP}$$

where GAD is water moved to a ground-water reservoir from a subsurface reservoir and RES is the current storage in the subsurface reservoir.

Predicted Effects of Impervious Surfaces on Runoff

Following calibration, it was possible to explain an average of 82 percent of the variation in streamflow measured at station 11166575 using PRMS. The mean of absolute deviation between measured and predicted discharge was 27 percent. Plots of measured discharge and predicted discharge for station 11166575 for the wet 1986 water year are shown in figure 5. At station 11166578, 66 percent of the variation in measured streamflow in 1985 and 85 percent in 1986 was explained by PRMS. The mean absolute deviation between measured and predicted discharge was 44 percent. Plots of measured and predicted discharge for the 1986 water year for station 11166578 are shown in figure 6. Measured and predicted runoff volumes for both stations are shown in table 4.

The ability of PRMS to explain variations in streamflow at both sites was somewhat limited by the amount of data available for model calibration. This was particularly true for the West Branch basin, where flow was not recorded during 1987. The accuracy of the calibrated model appears to be sufficient for purposes of this study; PRMS was not used to predict streamflow for periods when streamflow data were not collected. PRMS was used only to draw inferences about the response of the Permanente Creek basin to changes in land use.

Runoff upstream from station 11166578 is less flashy than that upstream from station 11166575. Flow apparently enters the channel from the subsurface reservoir more slowly in the West Fork than in Permanente Creek. The values of RCF and RCP, the coefficients used to route subsurface flow to streamflow, were two and five times greater in Permanente Creek than in the West Fork. Flow from the subsurface reservoir to the ground-water reservoir was also much faster in Permanente Creek basin than in the West Fork basin. The value of RSEP, the coefficient used to route subsurface flow to the ground-water reservoir, was three times greater in Permanente Creek than in the West Fork. The only other parameter that differed significantly between the Permanente Creek and West Fork basins was GSNK, the coefficient used to route ground water to the ground-water sink.

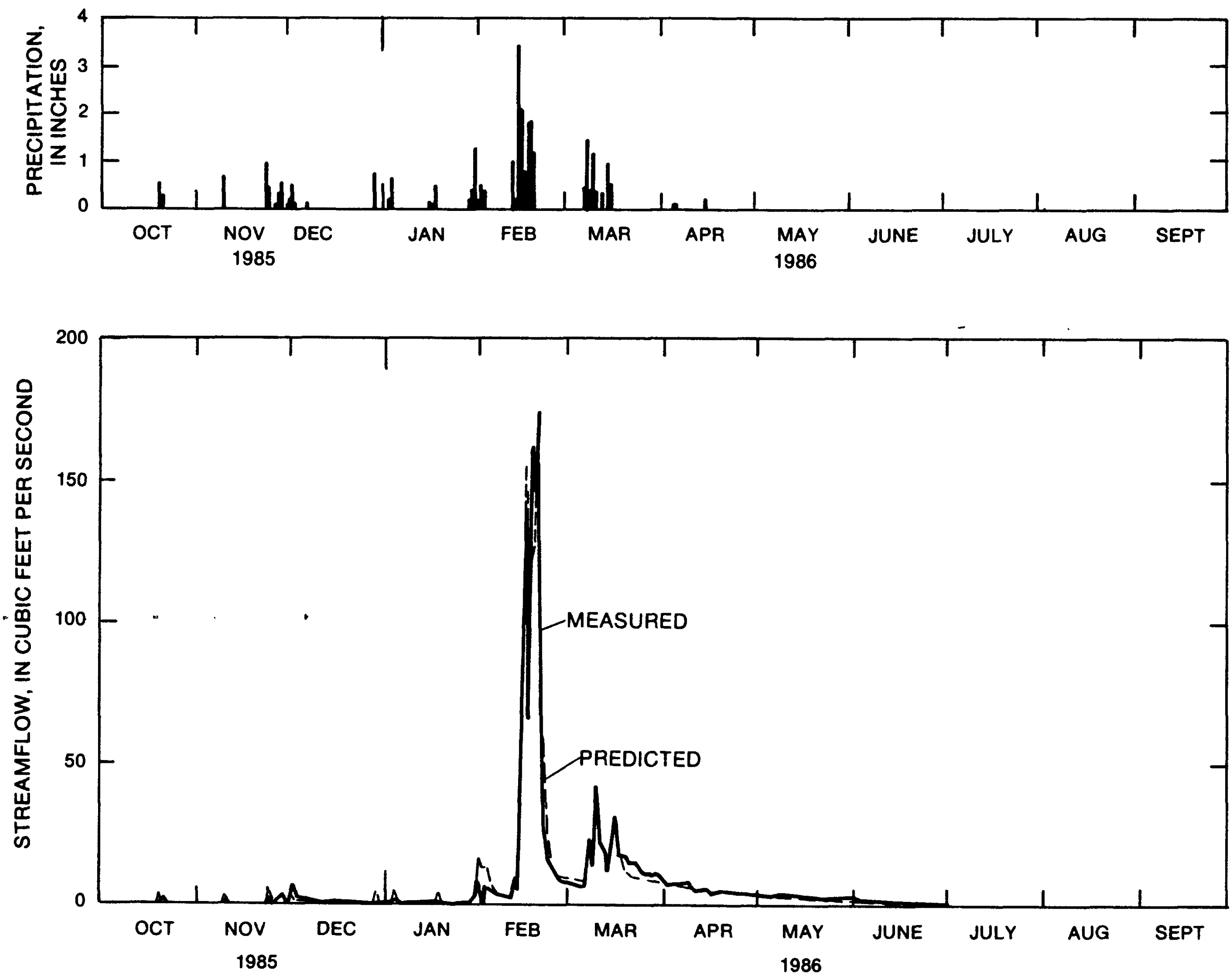

FIGURE 5.—Precipitation, measured discharge, and discharge predicted by the Precipitation-Runoff Modeling System for Permanente Creek near Monta Vista (11166575) during the 1986 water year.

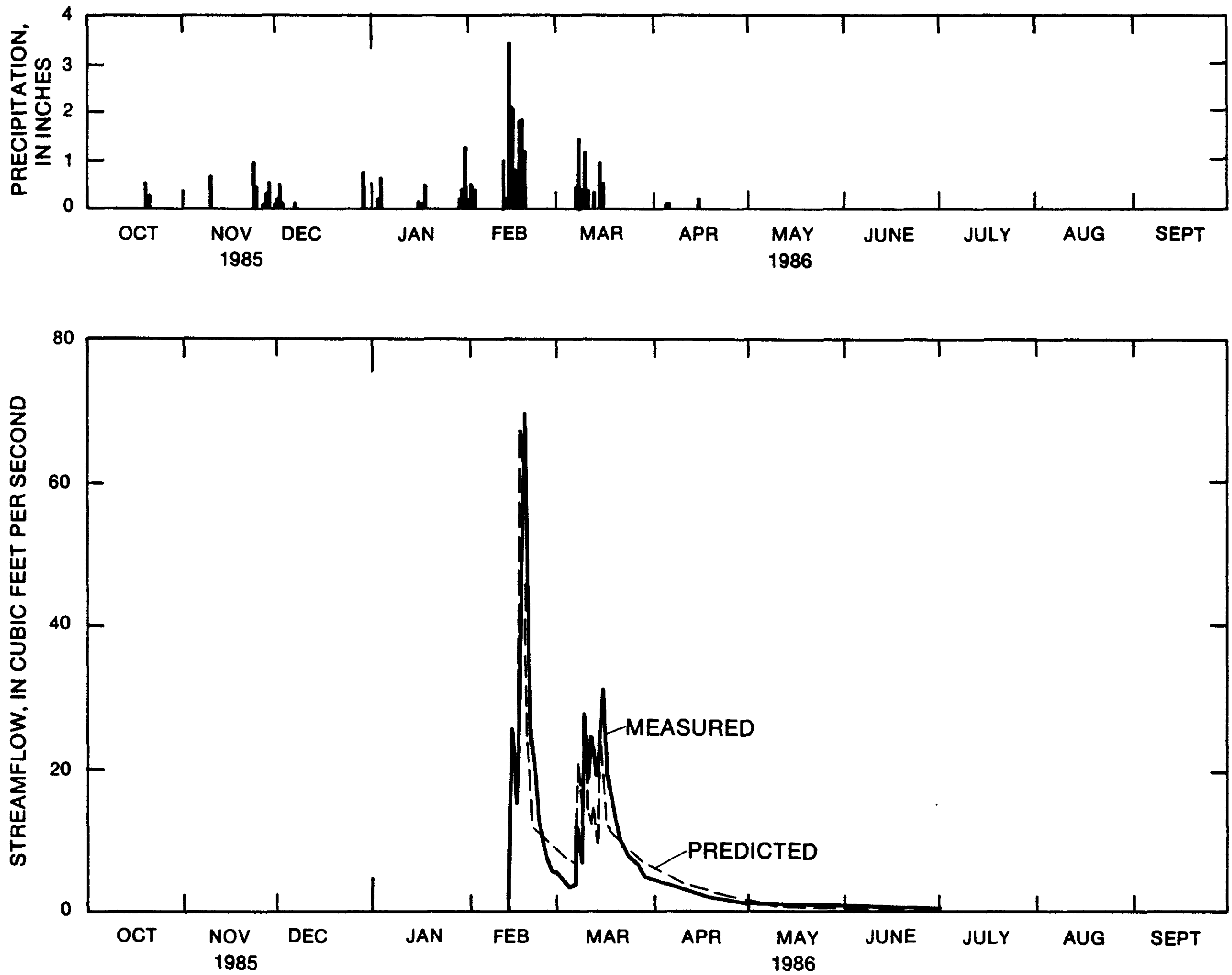

FIGURE 6.— Precipitation, measured discharge, and discharge predicted by the Precipitation-Runoff Modeling System for West Fork Permanente Creek near Monta Vista (11166578) during the 1986 water year.

Ground-water inflow to the ground-water sink was almost four times as fast in Permanente Creek basin as in the West Fork basin.

Variations in parameters necessary to predict adequately the streamflow in the Permanente Creek and West Fork Permanente Creek basins can be explained by the physical situations in the two basins. The large volume of alluvium along the West Fork channel apparently slows down the movement of water from hillslopes to stream channels. Where the channel is separated from hillslopes by relatively wide alluvial reaches, subsurface flow apparently enters the alluvium rather than directly entering the stream channel. Once in the alluvium, water moves slowly along low gradients into the channel.

The high seepage rate of water from the ground-water reservoir to the ground-water sink, which is implied by the high value for GSNK in the Permanente Creek basin, may be due to seepage of water into thick alluvial deposits in the reach immediately upstream from station 11166575. Station 11166575 is about 1 mile downstream from where the channel is incised into steep mountainous terrain. Comparing the loss of water to the

TABLE 4.--*Summary of measured and predicted runoff using Precipitation-Runoff Modeling System for gaging stations Permanente Creek near Monta Vista (11166575) and West Fork Permanente Creek near Monta Vista (11166578)*

Water	Measured runoff (in.)	Predicted runoff (in.)	Difference between predicted and measured (percent)
		Station 11166575	
1985	3.9	3.6	-8
1986	17.5	17.0	-3
1987	1.5	1.0	-33
		Station 11166578	
1985	0.7	0.6	-14
1986	10.6	14.6	+38
1987		No flow	

ground-water sink in the two study basins is difficult because PRMS cannot estimate storage in the ground-water reservoir prior to the onset of flow in the West Fork. The volume of water in the West Fork ground-water reservoir, therefore, is probably underestimated consistently because substantial ground-water storage occurs prior to onset of streamflow.

Effects of impervious surfaces associated with operation of the limestone quarry and cement plant were estimated by replacing parameters describing impervious surfaces in HRU P5 (Permanente Creek basin) with parameters describing natural soil and vegetation. The 15 percent of impervious surface was replaced with 0 percent of impervious surface, and instead of bare soil, HRU P5 was assumed to be covered by natural soil and vegetation. The authors were unable to simulate fully the potential land-use effects on soil hydraulic conductivity (KSAT) because adequate estimates of vertical hydraulic conductivities after soil surfaces were disrupted by human activities were not obtained. Hydraulic conductivities used for HRU P5 were, therefore, those for natural soils found in the HRU. It is likely that compaction and removal of vegetation cover has lowered vertical hydraulic conductivities in many areas of bare ground, spoils, and so forth. Human activities, therefore, might have increased surface runoff to a greater degree than indicated by PRMS simulations. Much of this effect on vertical hydraulic conductivity, however, has probably been accounted for during calibration for effective impervious areas. Runoff predicted before and after substituting parameters describing impervious surfaces with those describing natural surfaces for a dry year (1985) and a wet year (1986) are shown in figure 7.

PRMS simulations indicate that impervious surfaces associated with the limestone quarry and cement plant had the most striking effects on streamflow during storms that produce small to moderate amounts of runoff, as can be seen most easily by comparing streamflow predicted with and without impervious surfaces in HRU P5 during the early part of the 1985 water year (fig. 7*A*). PRMS predicts that there would have been little streamflow during the small storms of November and December 1984 if the impervious surfaces were not present in HRU P5. In contrast, comparison of streamflow predicted with and without impervious surfaces in HRU P5 during the wet periods of February and March 1986 indicates that runoff from impervious surfaces in HRU P5 had little effect on the magnitude of peak flows during this period (fig. 7*B*). Peak flows during this wet period were composed primarily of runoff from "variable source" saturated areas and (or) from subsurface flow, rather than from impervious surface runoff. Simulations after removal of impervious surfaces actually showed increased peak flow on a few days, apparently because water that would have flowed off impervious surfaces was available for infiltration and subsequent routing to subsurface flow and, thus, was

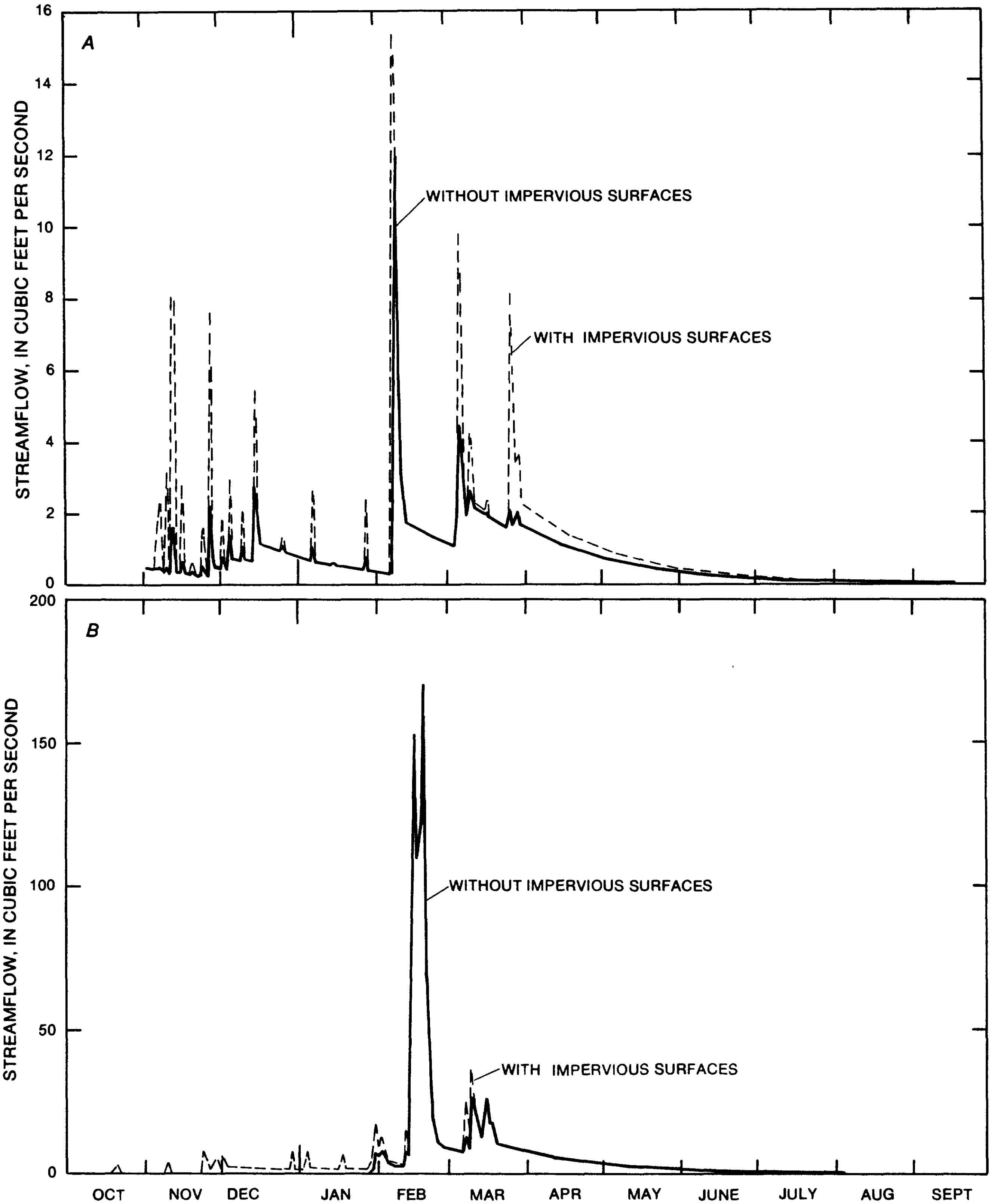

FIGURE 7.—Discharge predicted with and without impervious surfaces in the Permanente Creek basin, hydrologic response unit P5. *A*, 1985 water year (dry year). *B*, 1986 water year (wet year)

available to augment peak flows. PRMS simulations are in basic agreement with the findings of Harr and others (1975), Harr (1976), and Ziemer (1981), which were discussed earlier in this report.

PRMS results indicate that by removing much of the native vegetation in HRU P5, land use in Permanente Creek may have increased subsurface and ground-water flow during dry periods. The ground cover of HRU P5 was described as bare ground because, in addition to the many impervious surfaces, a high percentage of HRU P5 is covered by spoil piles, rilled areas, and other areas where vegetation has been removed or buried (fig. 3). The increased transpiration that occurs when bare soil is replaced with shrubs in the PRMS simulation results in a significant decrease in subsurface and ground-water flow during some periods. Effects of this additional transpiration are particularly pronounced during dry years, when increased transpiration apparently removes sufficient water from the upper soil zone to reduce significantly the number of days the soil zone fills with water. This, in turn, reduces the flow of water from the soil zone to the subsurface and ground-water reservoirs.

SEDIMENT YIELD

Measured Sediment Discharge

Total sediment discharge was measured at stations 11166575 and 11166578 during water years 1985-87 using standard practices of the U.S. Geological Survey (Guy and Norman, 1970). At station 11166575, total sediment discharge was measured during low and moderate flows using a DH-48 hand-held sampler on the downstream side of the weir installed to stabilize the stage-discharge relation at that site. These samples represent total sediment discharge because the sampler nozzle could be lowered to the bottom of the weir. When water discharges were larger and material that was too coarse to enter the DH-48 nozzle was moving, suspended-sediment discharge and bedload discharge were measured separately upstream of the weir. Suspended-sediment samples were collected using a DH-48 suspended-sediment sampler, and bedload samples were collected using a Helley-Smith bedload sampler. Bedload discharge for the peak discharge in 1986 was estimated using the Meyer-Peter and Mueller bedload equation (U.S. Bureau of Reclamation, 1960). Daily values of sediment discharge for 1985, 1986, and 1987 for both stations are published by the U.S. Geological Survey (Anderson, Markham, Shelton, Trujillo, and Grillo, 1987, 1988; Anderson, Markham, Shelton, and Trujillo, 1988). Total sediment loads and yields for individual water years are summarized in table 5. The average annual yield from the Permanente Creek basin was almost 15 times higher than the average annual yield measured from the West Fork basin.

TABLE 5.--*Measured sediment load and sediment yields at gaging stations Permanente Creek near Monta Vista (11166575) and West Fork Permanente Creek near Monta Vista (11166578)*

[Data are summarized from reports by Anderson, Markham, Shelton, Trujillo, and Grillo, 1987, 1988; Anderson, Markham, Shelton, and Trujillo, 1988. ton/mi^2, tons per square mile]

	Station 11166575		Station 11166578	
Water year (1)	Sediment load (tons) (2)	Sediment yield (ton/mi^2) (3)	Sediment load (tons) (4)	Sediment yield (ton/mi^2) (5)
1985	796	206	1.2	0.4
1986	53,240	13,792	2,870	963
1987	140	36	0	0
Total	54,176	14,034	2,871	963
Average	18,100	4,680	957	321

In addition to the amount of sediment that passed stations 11166575 and 11166578, some sediment transported by the two streams was trapped in impoundments within the two drainage basins. In addition to the settling basin constructed by the Kaiser Cement Corporation 0.5 mile upstream from station 11166575, there is a much smaller (0.17 acre) settling basin about 1.5 miles upstream from station 11166575. Two small settling basins also were constructed in the West Fork basin 1.1 and 1.5 miles upstream from station 11166578 to aid ground-water recharge. The location of the settling basins are shown in figure 2. Sediment accumulation in the Permanente Creek settling basin 0.5 mile above station 11166575 was estimated from records of cleaning operations supplied by the Kaiser Cement Corporation. Sediment accumulation in the two West Fork settling basins was estimated from repeated surveys of three cross sections established across each basin. Channel cross sections installed to estimate accumulation in the upper Permanente Creek settling basin were destroyed by heavy equipment in 1986. Although sediment accumulation in this small settling basin was assumed to be small, compared with total sediment load from the drainage basin, its effect cannot be assessed.

Measured volumes of sediment that accumulated in the three impoundments were converted to mass using the bulk densities of samples of the accumulated material. During 1985-87 a total of 10,400 yd^3 of sediment, weighing an average of 2,700 lb/yd^3, were removed from the Permanente Creek settling basin 0.5 mile above station 11166575 (Randy Talley, Santa Clara Valley Water District, written commun., 1986). The total weight of this sediment was 14,000 tons. An estimated total of 1,400 tons of sediment accumulated in the West Fork settling basins between 1985 and 1987. Because of the short distance between the downstream settling basin on Permanente Creek and station 11166575, it seems reasonable to assume that most of the 14,000 tons of sediment removed from the settling basin would have passed station 11166575 during the study. Therefore, true sediment production from the drainage basin upstream from station 11166575 during the study was probably closer to 68,000 tons than to the 54,176 tons shown in table 5. Because the two settling basins in the West Fork basin are located considerable distances upstream from station 11166578, it is questionable how much of the accumulated sediment actually would have been transported past station 11166578 during this study. At least some of this sediment probably would have been deposited in the channel below the settling basins, because net deposition was measured in the channel during the study. (See section on "Sequential surveys of channel cross sections.") In comparing yields measured at station 11166575, the most conservative approach would be to assume that all sediment that accumulated in the West Fork settling basins would have passed station 11166578. Under this assumption, the estimated total sediment load past station 11166578 would have been about 4,300 tons. Using these estimates, the average annual sediment yield from Permanente Creek was 12 times greater than the average yield from the West Fork Permanente Creek [5,870 $(ton/yr)/mi^2$ compared with 480 $(ton/yr)/mi^2$].

Regional Comparison

To illustrate how sediment yields from the Permanente Creek and West Fork Permanente Creek basins compare with other nearby basins, the available literature has been compiled describing sediment yields from seven drainage basins in the Santa Cruz Mountains and surrounding areas (table 6). Locations of these seven streams are shown in figure 1. The following discussion briefly summarizes the studies included in table 6.

Brown (1973) described sediment transport in two streams on the west side of the Santa Cruz Mountains, where annual rainfall is generally greater than in the Permanente Creek basin. During 1970-71, sediment yield in Newell Creek (fig. 1),

TABLE 6.--*Results of previous studies of sediment yields in the Santa Cruz Mountains and surrounding areas*

[Average sediment yield is expressed as tons per square mile per year]

Study author and year	Study area (fig. 1)	Period of study	Type of sediment data	Basin land-use conditions	Average sediment yield
Brown (1973)	Newell Creek	1970-71	Reservoir sedimentation	Relatively undisturbed	1,100
Brown (1973)	Zayante Creek	1970-71	Suspended sediment	Impacted by roadbuilding	2,570
Knott (1973)	Colma Creek	1969-70	Total sediment	Open space	382
Knott (1973)	Colma Creek	1969-70	Total sediment	Impacted by construction	32,800
Macy (1976)	San Lorenzo River	1975	Suspended sediment	Relatively undisturbed	1,178
Knott and others (1978)	Calabazas Creek	1973-75	Total sediment	Partially developed gravel pit in upper basin	3,080
Porterfield (1980)	San Francisquito Creek	1957-66	Suspended sediment	Partially developed, with slight active disturbance	224

estimated from measurements of sediment accumulation in Loch Lomond Reservoir, was 1,100 (ton/yr)/mi^2. The Newell Creek drainage basin was fairly undisturbed at the time of the study. Measurements of suspended-sediment discharge at Zayante Creek during 1970-71 indicated an average suspended-sediment yield of 2,570 (ton/yr)/mi^2. The Zayante Creek basin (fig. 1) had been disturbed by roadbuilding just prior to Brown's study.

Knott (1973) investigated sediment yields in relation to land use in the Colma Creek basin (fig. 1) during 1964-71. For water years 1969-70, he found that total sediment yields from open space areas ranged from 311 to 452 (ton/mi^2)/yr. For the same period, Knott reported that total sediment yields from areas affected by construction ranged from 26,200 to 39,300 (ton/yr)/mi^2. These results indicate an increase in sediment yields of two orders of magnitude due to disturbance related to land use.

Macy (1976) reported on a 1-year (1975) study of suspended-sediment discharge in the headwaters of the San Lorenzo River on the west side of the Santa Cruz Mountains. He determined a suspended-sediment yield of 1,178 (ton/mi^2)/yr. His study area was fairly undisturbed.

Knott and others (1978) studied sediment transport during water years 1973-75 in the Calabazas Creek basin (fig. 1), which is 7 miles south of the Permanente Creek basin and similar in terms of climate, geology, and physiography. The total sediment yield for the entire drainage basin, including sediment deposited in a debris basin, ranged from 2,125 to 4,026 (ton/yr)/mi^2. Much of the sediment reaching the downstream gaging station originated from a small tributary basin that included a large gravel pit adjacent to the stream channel. Knott and others (1978) determined that this basin had a total sediment yield that ranged from four to nine times higher than any other part of the Calabazas Creek basin.

Porterfield (1980) reviewed and summarized sediment data for streams draining into San Francisco Bay, including San Francisquito Creek (fig. 1). The San Francisquito Creek basin is partly developed, but at the time of Porterfield's study it was affected only slightly by construction activity and similar land uses. The average suspended-sediment yield estimated by Porterfield (1980) for San Francisquito Creek between 1957 and 1966 was 224 (ton/yr)/mi^2.

These studies include diverse periods, basins, and types of data, but they provide a range of sediment-yield data with which to compare data from Permanente Creek and West Fork Permanente Creek (table 5). Average sediment yields from nearby undisturbed areas ranged from 224 to 1,178 (ton/yr)/mi^2. Sediment yields from basins disturbed, to a large extent, by land uses ranged from 2,125 to 39,300 (ton/yr)/. Clearly the average annual sediment yield determined for the West Fork Permanente Creek [321 (ton/yr)/mi^2 measured or 480 (ton/yr)/mi^2 estimated after considering deposition in settling basins] falls into the range for undisturbed basins, and the average annual yield determined for Permanente Creek [4,678 (ton/yr)/mi^2 measured or 5,800 (ton/yr)/mi^2 estimated after considering deposition in the settling basin] is within the range for disturbed basins.

Frequency of Sediment Discharge

Data in table 5 illustrate the importance of periods of high streamflow on sediment transport in Permanente Creek. Ninety-eight percent of the sediment load at station 11166575 and more than 99 percent of the sediment load at station 11166578 between 1985 and 1987 were measured during the wet 1986 water year. Ninety percent of all sediment transport between 1985 and 1987 took place in 13 days in the Permanente Creek basin and in 8 days in the West Fork basin.

Sediment Sources

Records of sediment transport at the two gaging stations used in this study provide a measure of the total sediment output from the Permanente Creek and West Fork Permanente Creek basins but do not indicate the sources of that sediment. An evaluation of potential sediment sources in the two basins was needed to assess the effects of land-use disturbances and to provide information useful in designing sediment-control measures. Mapping of erosional landforms, sequential surveys of channel cross sections, and synoptic sampling of sediment discharge were used to evaluate potential sediment sources in the Permanente Creek and West Fork Permanente Creek basins.

Mapping of Erosional Landforms

Erosional landforms are distinct features on the Earth surface that are caused either by mass movement, human activities, or fluvial erosion. Landforms analyzed in the study area are limited to those that were mapped by J.H. Galton (U.S. Geological Survey, written commun., 1985) on aerial photographs taken in calendar years 1948, 1968, and 1984. The 1948 photographs were taken at a scale of 1:23,600, the 1968 photographs at 1:30,000, and the 1984 photographs at 1:8,000. The 1948 and 1968 photographs are black-and-white, but the 1984 photographs are color. Using U.S. Geological Survey 1:24,000-scale topographic maps (Cupertino and Mindego Hill quadrangles) as a base, maps were prepared showing location and extent of erosional landforms as they existed in 1948, 1968, and 1984. The base maps were enlarged to a scale of 1:8,000.

Stable and active landslides, rapidly eroding watercourses, bare ground, spoils and storage piles, impervious areas, and rilled areas were all mapped by Galton. Landslide types considered included block slides, debris slides, debris avalanches, and debris flows.

Landslide classification follows that of Varnes (1978). Rapidly eroding watercourses were defined as steep, low-order channels displaying raw, eroding banks. All areas mapped as bare ground, spoils and storage piles, impervious areas, and rills were considered directly related to human activity and are termed artificial landforms. The association of spoils and storage piles with human activity is obvious. Impervious surfaces, bare ground, and rills also were considered artificial. Galton noted that these features are generally related to human activity, a relation which was confirmed when the locations of these features were examined on the aerial photographs. Landslides were considered the result of human activity if they were immediately adjacent to, or within, some other artificial landform, or if they were crossed by roads and were inactive prior to road construction.

The areas of individual erosional landforms were determined from the maps using a compensating polar planimeter. For erosional landforms that were individually too small to measure accurately with a planimeter, a composite tracing of several such landforms was drawn, and the total area of the composite was measured.

Because of the implications for direct sediment delivery, lengths of streambanks adjacent to erosional landforms were measured in both Permanente Creek and West Fork Permanente Creek basins. Only stream channels designated by blue lines on the 1:24,000 scale topographic maps were considered. Lengths were measured with a map wheel on each of the three maps. Left and right banks were measured separately.

Areas in each erosional landform mapped by Galton in the Permanente Creek and West Fork Permanente Creek basins are shown in table 7. Areas of artificial landforms for both basins are shown in table 8. Impervious areas are not included in table 8 because, although they are a direct measure of the effects of human activity, they are not necessarily a direct source of sediment. Impervious areas, as mapped by Galton, included rooftops, paved roads, unpaved roads, and parking lots. Tables 9 and 10 show the length of streambanks next to both natural and artificial erosional landforms in the Permanente Creek and West Fork Permanente Creek basins.

Sequential Surveys of Channel Cross Sections

Erosion along Permanente Creek and West Fork Permanente Creek was documented by repeated surveys of monumented stream-channel cross sections installed by personnel of the Santa Clara Valley Water District in 1985. Cross sections span the active channel and were located by establishing a line of sight perpendicular to the channel. Cross-section elevations were referred only to arbitrary local datums and were not tied to sea level. Cross sections were resurveyed in 1986 and 1987 to determine changes in cross-sectional area owing to deposition or erosion. Surveying was done with a level, surveying rod, and cloth tape. Channel cross sections are located in figure 8 and shown in figure 9.

TABLE 7.--*Areas of erosional landforms in the Permanente Creek and West Fork Permanente Creek basins, 1948, 1968, and 1984*

[All values are in acres. From mapping by J.H. Galton, U.S. Geological Survey, written commun., 1985]

Calendar year	Stable landslides				Active landslides			
	Block slides	Debris flows	Debris avalanches	Debris slides	Block slides	Debris flows	Debris avalanches	Debris slides
Permanente Creek basin								
1948	134	6	0	0	0	0	11	6
1968	173	2	0	2	6	0	5	6
1984	173	5	0	7	9	1	5	29
West Fork Permanente Creek basin								
1948	188	0	32	0	0	0	2	0
1968	180	0	22	0	3	0	6	5
1984	148	0	12	7	0	0	2	12

Calendar year	Fluvial		Bare ground	Bare slopes	Spoils piles	Rills	Impervious areas
	Unstable stream-banks	Actively eroding watercourses					
Permanente Creek basin							
1948	20	20	14	87	15	5	49
1968	15	18	40	37	59	4	30
1984	10	12	84	17	101	39	84
West Fork Permanente Creek basin							
1948	12	28	5	0	0	0	2
1968	5	20	5	5	0	0	20
1984	7	2	15	2	0	0	22

TABLE 8.--*Areas of potential sediment sources considered to have been affected by human activity in the Permanente Creek and West Fork Permanente Creek basins, 1948, 1968, and 1984*

[All values are in acres. Based on erosional landform mapping by J.H. Galton, U.S. Geological Survey, written commun., 1985]

Calendar year	Bare ground	Bare slopes	Spoils piles	Rills	Artificially generated active landslides	Actively eroding watercourses
Permanente Creek basin						
1948	14	87	15	5	6	0
1968	40	37	59	4	10	1
1984	84	17	101	39	30	2
West Fork Permanente Creek basin						
1948	5	0	0	0	0	0
1968	5	5	0	0	2	0
1984	15	2	0	0	11	0

TABLE 9.--*Lengths of streambanks adjacent to natural and artificial erosional landforms in the Permanente Creek basin, 1948, 1968, and 1984*

[All values are in miles]

Calendar year	Natural landforms				
	Stable landslides				Active landslides
	Block slides	Debris flows	Debris avalanches	Debris slides	
1948	0.55	0.02	0	0	0.09
1968	.61	.00	0	0	.04
1984	.58	.04	0	0	.13

Calendar year	Artificial landforms					
	Bare ground	Bare slopes	Spoils piles	Rills	Impervious areas	Active landslides
1948	0	0.40	0	0.11	0.32	0.05
1968	.21	0	.55	0	.02	.02
1984	.24	0	1.10	.04	1.13	.25

TABLE 10.--*Lengths of streambanks adjacent to natural and artificial erosional landforms in the West Fork Permanente Creek basin, 1948, 1968, and 1984*

[All values are in miles]

Calendar year	Natural landforms				
	Stable landslides				Active landslides
	Block slides	Debris flows	Debris avalanches	Debris slides	
1948	0.98	0.83	0.02	0	0
1968	1.30	.87	0	0	.08
1984	1.38	0	0	.02	0

Calendar year	Artificial landforms					
	Bare ground	Bare slopes	Spoils piles	Rills	Impervious areas	Active landslides
1948	0.58	0	0	0	0.02	0
1968	0	0	0	0	.02	0
1984	.30	0	0	0	.02	.03

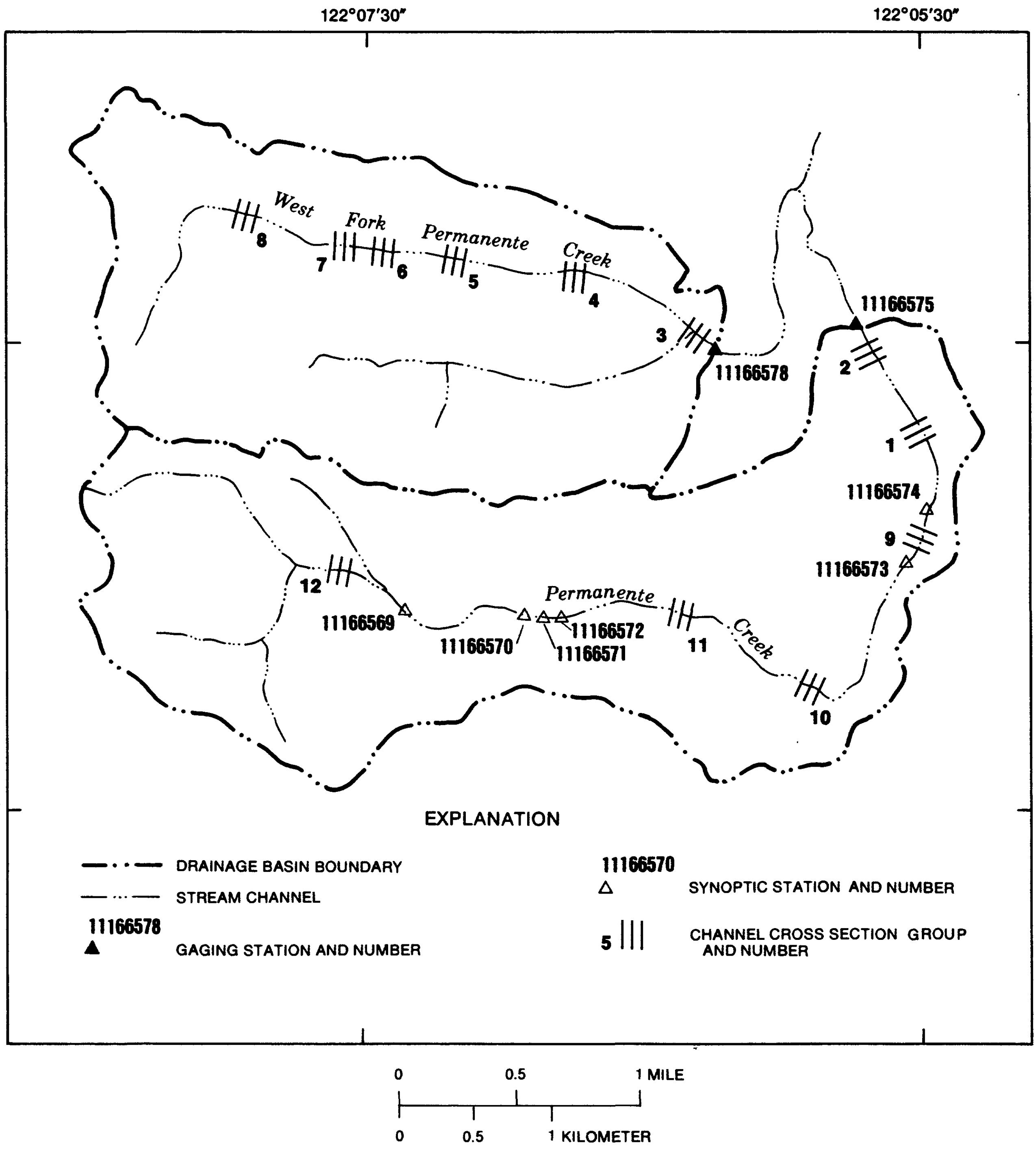

FIGURE 8.— Location of stream-channel cross sections and synoptic sampling locations in the Permanente Creek and West Fork Permanente Creek basins.

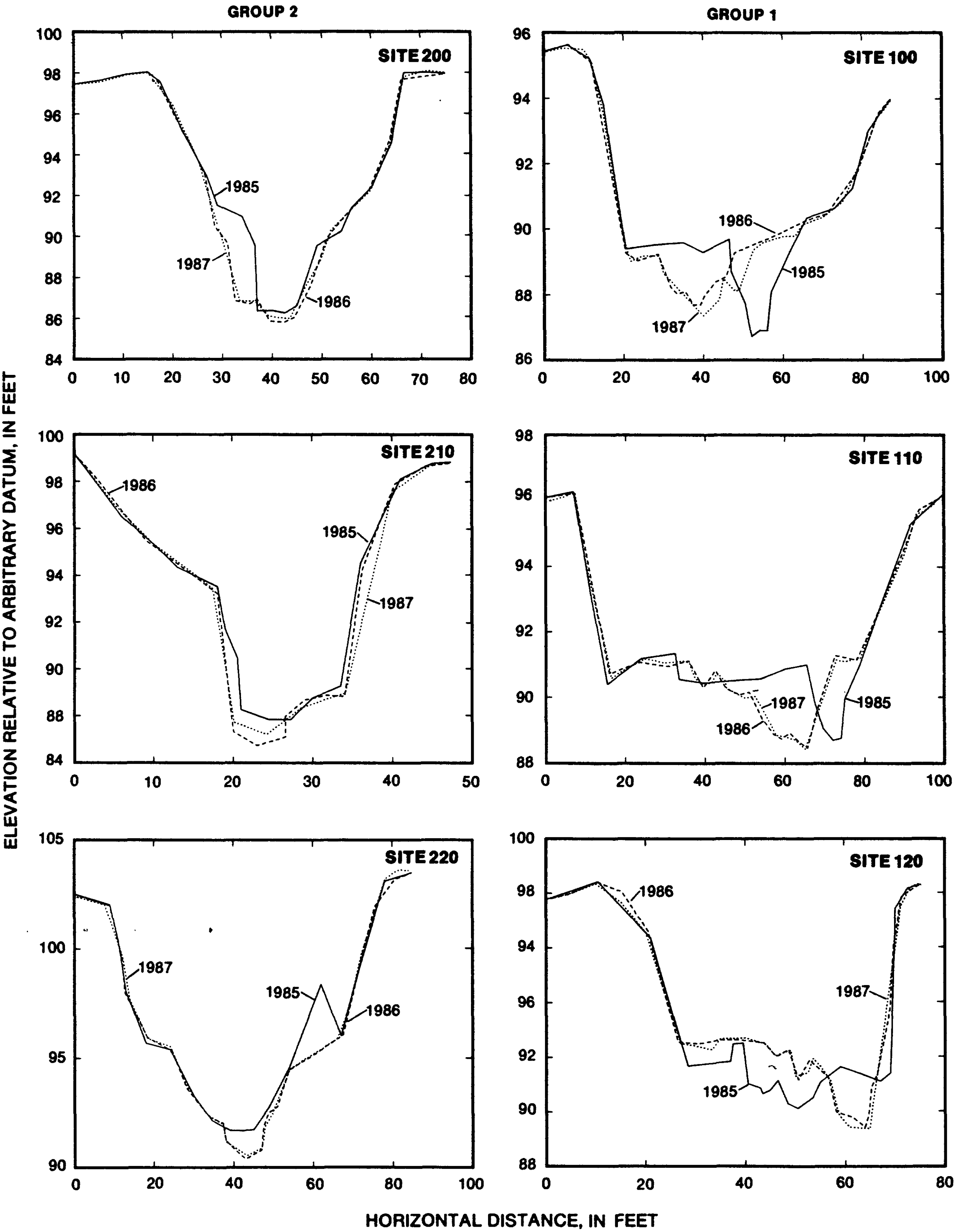

FIGURE 9.– Cross-sectional groups. View is downstream. Cross-section locations are shown in figure 8. Site numbers were assigned by the Santa Clara Valley Water District. Hundreds digits of site numbers correspond to cross-sectional group number. Tens digits correspond to one-up number of cross section within group. Ones digit is always zero and has no meaning. Cross-sectional groups 11 and 12 are not represented because sites were destroyed.

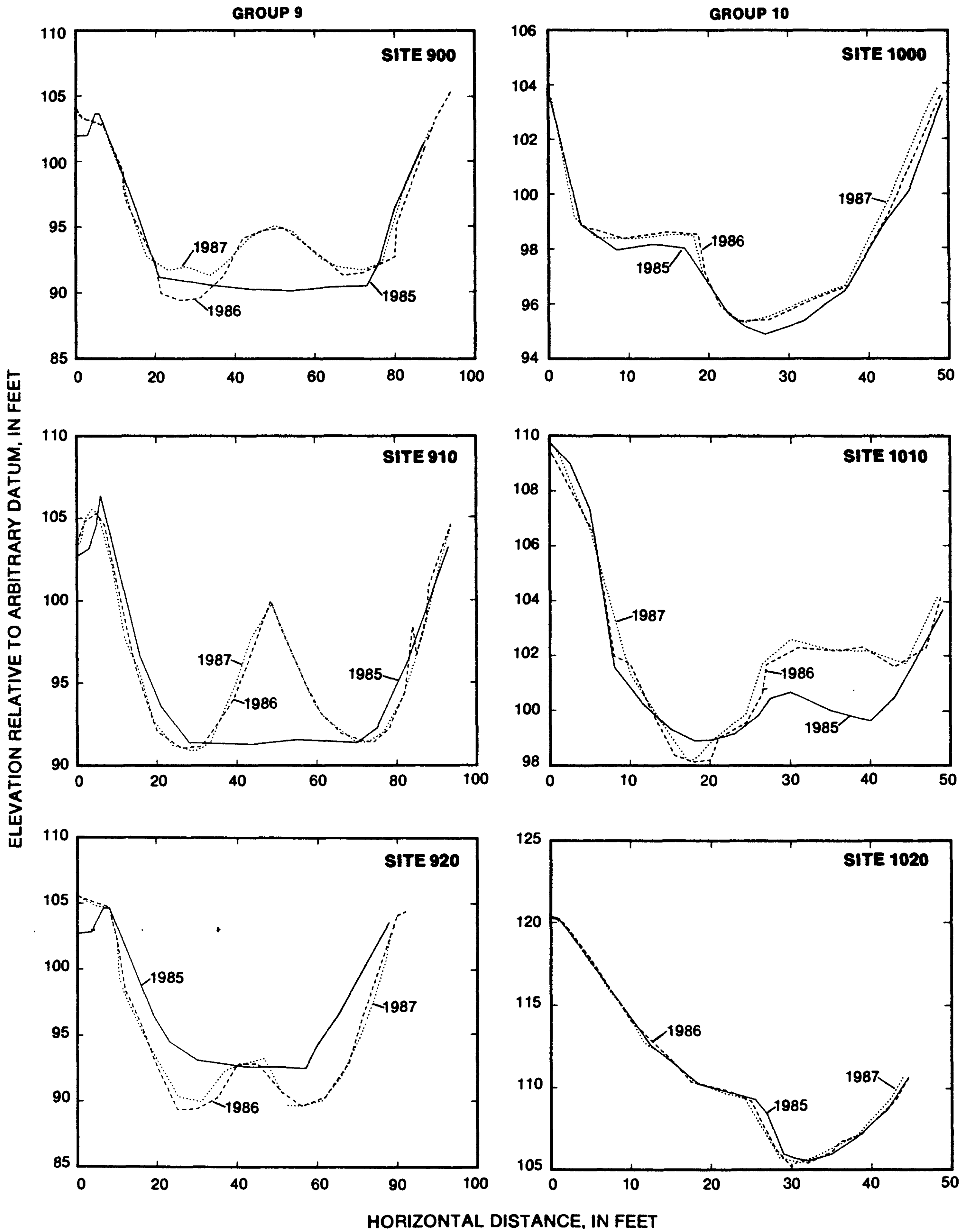

FIGURE 9.— Channel cross sections—Continued.

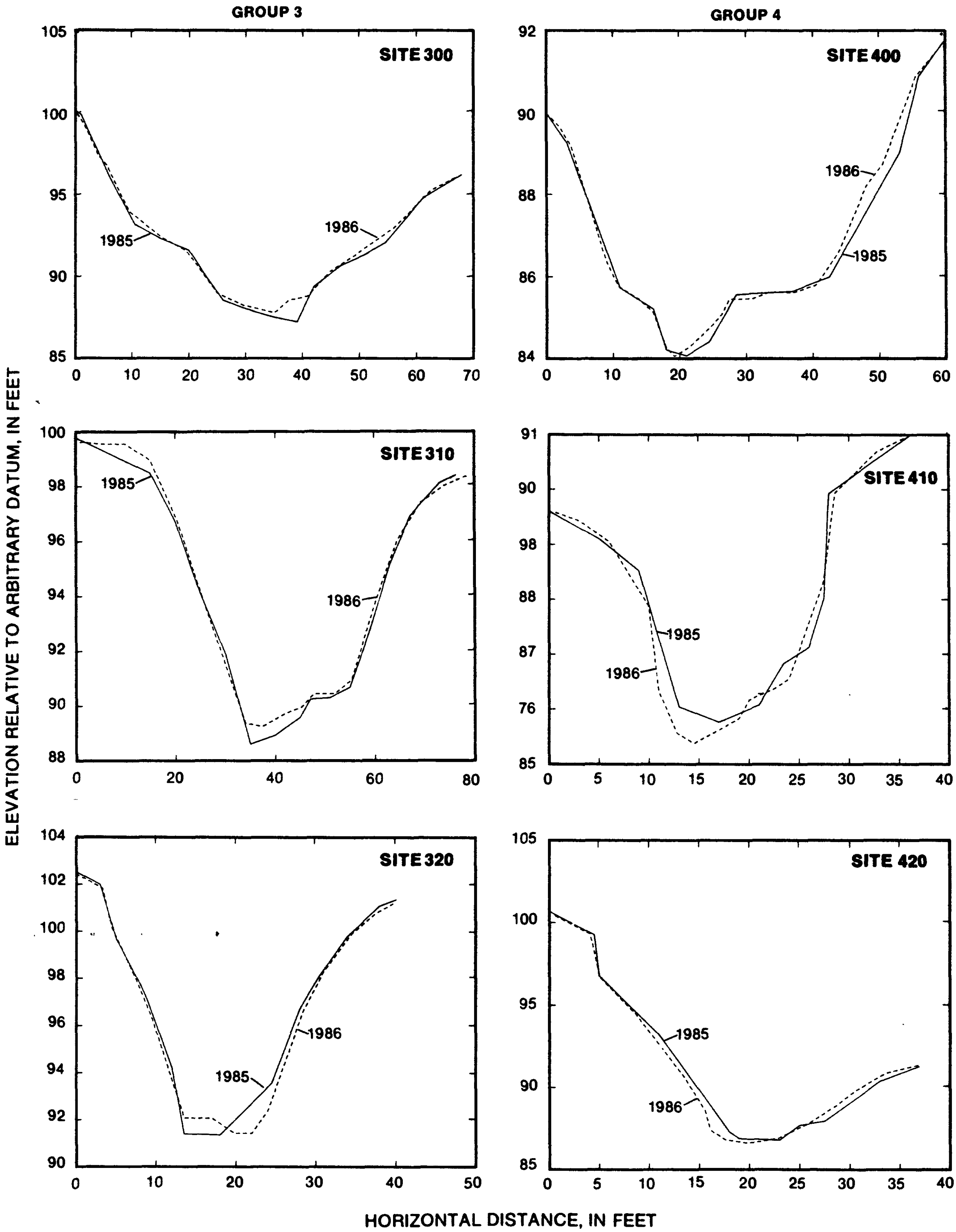

FIGURE 9.— Channel cross sections—Continued.

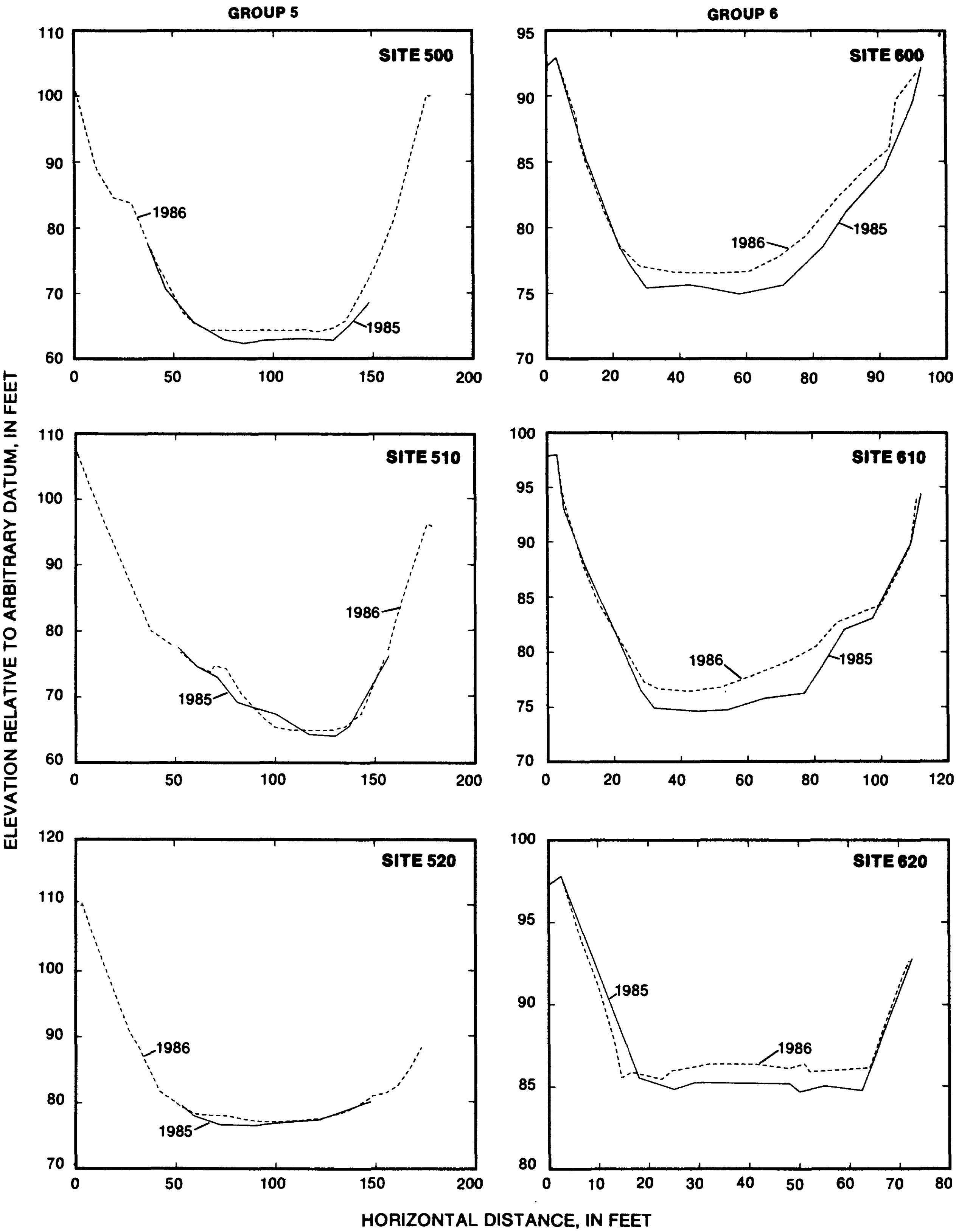

FIGURE 9.— Channel cross sections—Continued.

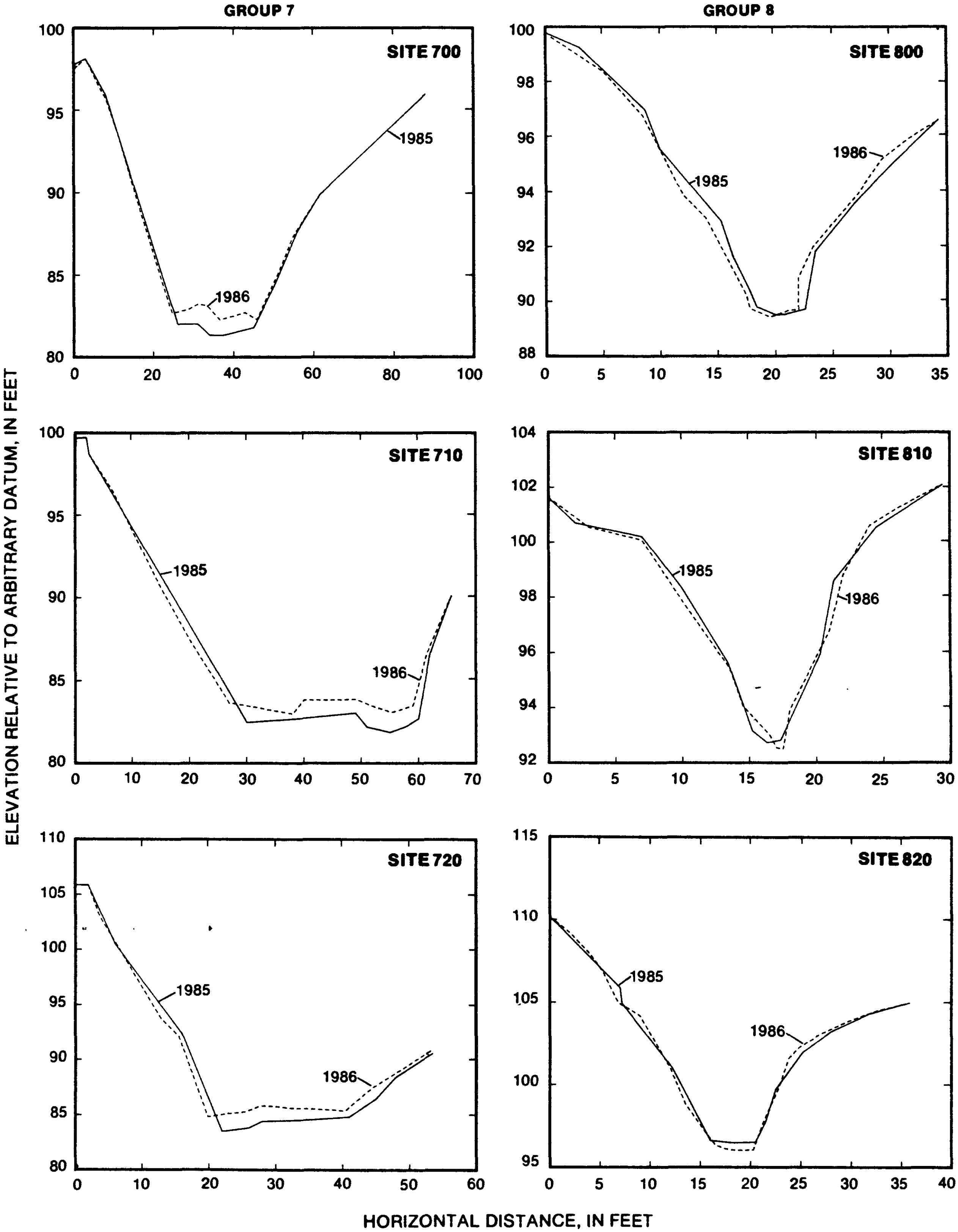

FIGURE 9.— Channel cross sections—Continued.

Changes in channel configuration between 1985 and 1986 and between 1986 and 1987 were measured by the dot-grid method to calculate changes in the area of left and right banks and in the streambed. This method involves placing a transparent grid over a cross-section plot and counting the number of squares, or "dots," that fall within the area of interest. By multiplying the number of squares by the cross-section scale represented by one "dot," the area is computed. Area changes for West Fork cross sections between 1986 and 1987 were not computed because the West Fork did not flow during the year. Total volumes of channel erosion and deposition for 1985-86 and 1986-87 were determined first by calculating average area changes for 1985-86 and 1986-87 at each group of three cross sections. These group averages then were multiplied by half the distance to the cross-sectional group immediately upstream plus half the distance to the cross-sectional group immediately downstream from the cross-sectional groups. For the farthest upstream and downstream cross-sectional groups for the channels considered, group averages were multiplied by only half the distance to the next cross-sectional group. Only cross-sectional groups representative of the natural channel (1, 2, 10 along Permanente Creek and 3, 4, 7, 8 along the West Fork) were used in volume calculations; cross sections located in ponds or settling basins were not used.

Volumes computed using the methods described above were converted to units of mass by multiplying the volumes by the bulk density measured for bank and bed material samples collected near each gaging station. These samples were collected by driving a metal can into the stream bank and bed. Samples were transferred to canvas bags, oven dried at about 65 °C (degrees Celsius) for 8 hours, and weighed. Bulk densities were calculated as sample mass divided by the volume of the can used to collect the sample. Samples also were sieved through a 2-mm (millimeter) sieve with a mechanical shaker for about 15 minutes, and the material remaining on the sieve was then weighed. The percentage of each sample finer than 2 mm intermediate grain diameter was determined by subtracting the mass of material that remained on the sieve from the total sample mass and dividing by the total sample mass.

Average changes in area for each cross-sectional group along Permanente Creek between March 1985 and July 1987 are shown in table 11. Changes for the West Fork between March 1985 and September 1986 are shown in table 12. Bulk-density determinations and percentages finer than 2-mm intermediate grain diameter for bank and bed material samples collected near stations 11166575 and 11166578 are shown in table 13. Changes between cross-section surveys done in March 1985 and September 1986 were used to estimate channel changes that occurred during the 1986 water year. Changes between cross-section surveys done in September 1986 and July 1987 were used to estimate channel changes that occurred during the 1987 water year. Estimated volumes and masses of sediment stored in or eroded from the Permanente Creek lower channel during water years 1986 and 1987 are shown in table 14. Heavy equipment operating in the main channel destroyed cross sections at sites 11 and 12 following the original 1985 survey, and no area changes could be computed for these sites. Estimated sediment volumes are, therefore, computed only for the channel between cross-sectional groups 2 and 10, and no extrapolation to the channel farther upstream was attempted. Estimated volumes and masses of sediment stored in or eroded from the West Fork lower channel are shown in table 15.

Net deposition was measured along Permanente Creek during the study. An estimated 46 and 1,500 tons of sediment were deposited along the banks and bed, respectively, during water year 1986. During water year 1987, an estimated 326 tons were deposited in banks and 369 tons

TABLE 11.--*Changes in cross-sectional area at monumented channel cross sections, Permanente Creek, between March 1985 and July 1987*

[All values are in square feet. Data represents difference between years in cross-sectional measurements. Positive numbers indicate net erosion; negative numbers indicate net deposition. Left and right banks are defined looking downstream]

Cross-sectional group	Left bank	Bed	Right bank
March 1985 to September 1986			
1	-1	-1	-1
2	2	13	9
9	24	-48	27
10	-1	-10	1
September 1986 to July 1987			
1	0	3	0
2	1	-2	0
9	2	-14	1
10	-3	-1	0

were eroded from the bed. Net channel deposition during the study was, therefore, about 1,500 tons. Furthermore, the stream channel between cross-sectional groups 2 and 10 seems to be a negligible source of the sediment passing station 11166575 during water years 1986-87. Net deposition was also measured along the West Fork channel. An estimated total of 3,940 tons of sediment were deposited along the West Fork channel in the 1986 water year (table 15). The mass of sediment stored in the West Fork during water year 1986 is more than two times greater than that stored along Permanente Creek. In terms of channel length, there was about 0.20 ton per foot stored along Permanente Creek in 1986 and about 0.35 ton per foot stored along the West Fork.

TABLE 12.--*Changes in cross-sectional area at monumented channel cross sections, West Fork Permanente Creek, between March 1985 and September 1986*

[All values are in square feet. Data represents difference between years in cross-sectional measurements. Positive numbers indicate net erosion; negative numbers indicate net deposition. Left and right banks are defined looking downstream]

Cross-sectional group	Left bank	Bed	Right bank
March 1985 to September 1986			
3	-2	-3	1
4	1	2	-3
5	-3	-44	-10
6	0	-67	-36
7	9	-23	-4
8	2	0	-1

TABLE 13.--*Bulk density and percentage of sediment finer than 2 millimeters for streambank and bed samples taken at Permanente Creek near Monta Vista (11166575) and West Fork Permanente Creek near Monta Vista (11166578)*

[ton/ft^3, tons per cubic foot; mm, millimeter]

Station No. (fig. 2)	Banks	
	Bulk density (ton/ft^3)	Percent finer than 2 mm
11166575	0.035	96
11166578	.023	86
	Bed	
11166575	0.051	25
11166578	.047	59

TABLE 14.--*Estimated changes in storage of sediment along the lower channel of Permanente Creek, based on changes in cross-sectional areas at monumented cross sections between March 1985 and July 1987*

[Bank area changes are reported as the sum of left and right bank changes. Positive numbers indicate erosion; negative numbers indicate deposition. Bank and bed volumes, in cubic feet, were converted to storage, in tons, by multiplying by the bulk densities shown in table 13. Totals have been rounded to three significant figures. Left and right banks defined looking downstream. ft^2, square feet; ft^3, cubic feet]

Cross-sectional group	Change in bank area (ft^2)	Change in bed area (ft^2)	Channel length (feet)	Change in bank volume (ft^3)	Change in bank storage (tons)	Change in bed volume (ft^3)	Change in bed storage (tons)
			March 1985 to September 1986				
2	11	13	590	6,490	227	7,670	391
1	-2	-1	3,900	-7,800	-273	-3,900	-199
10	0	-10	3,300	0	0	-33,000	-1,680
Total			7,790		-46		-1,490
			September 1986 to July 1987				
2	1	-2	590	590	21	-1,180	-60
1	0	3	3,900	0	0	11,700	597
10	-3	-1	3,300	-9,900	-347	-3,300	-168
Total			7,790		-326		369

TABLE 15.--*Estimated changes in storage of sediment along the lower channel of the West Fork Permanente Creek, based on changes in cross-sectional areas at monumented cross sections between March 1985 and September 1986*

[Bank area changes are reported as the sum of left and right bank changes. Positive numbers indicate erosion; negative numbers indicate deposition. Bank and bed volumes, in cubic feet, were converted to storage, in tons, by multiplying by the bulk densities shown in table 13. Totals have been rounded to three significant figures. Left and right banks defined looking downstream. ft^2, square feet; ft^3, cubic feet]

Cross-sectional group	Change in bank area (ft^2)	Change in bed area (ft^2)	Channel length (feet)	Change in bank volume (ft^3)	Change in bank storage (tons)	Change in bed volume (ft^3)	Change in bed storage (tons)
			March 1985 to September 1986				
3	-1	-3	1,500	-1,500	-35	-4,500	-212
4	-2	2	4,100	-8,200	-189	8,200	385
7	5	-23	3,800	19,000	437	-87,400	-4,110
8	1	0	1,200	1,200	28	0	0
Total			10,600		241		-3,940

Synoptic Sampling of Sediment Discharge

Limited synoptic sediment sampling was done during several storms in an attempt to define more accurately the sources of sediment in the Permanente Creek basin. Streamflow measurements were made at the miscellaneous sites using methods described by Rantz (1982), and suspended-sediment samples were collected using the EWI method (U.S. Geological Survey, 1977). Sampling-site locations are shown in figure 8. Suspended-sediment discharge was computed using streamflow and suspended-sediment concentration following methods described by Porterfield (1972). Storm-sampling results are shown in table 16. Samples represent instantaneous discharge at the times indicated. Measured suspended-sediment discharge ranged from 0.47 ton/d at station 11166572 on January 30, 1986, to 4,830 ton/d at station 11166573 on February 14, 1986.

Effects of Natural and Artificial Landforms on Sediment Discharge

Natural and Artificial Erosional Landforms

The amount of area affected by the various erosional landforms in Permanente Creek and West Fork Permanente Creek basins provides the most direct means of assessing potential sediment sources in each basin. The actual volumes of sediment coming from each landform, however, are unknown. A total of 307 acres of active landslides, fluvial landforms, bare ground, bare slopes, spoils piles, and rills were mapped on the 1984 aerial photographs of the Permanente Creek basin (table 7). Of these 307 acres of active erosional landforms, 273 acres (89 percent) were composed of artificial features (tables 7 and 8; fig. 10). By contrast, artificial landforms occupied only 28 acres (12 percent of landform area) in the West Fork basin. Not only are artificial landforms abundant in the Permanente Creek basin, but many of them are situated in areas where sediment delivery to stream channels is probably high. A total of 1.6 miles of main-channel streambanks are immediately adjacent to artificial landforms (table 9), of which 1.1 miles were adjacent to spoils piles. The loose, unconsolidated material contained in these steeply sloping piles seems to be a readily available source of sediment. Many of these spoils piles are rilled and gullied, and mobilized sediment is easily transported to active stream channels.

Although natural erosional landforms occupy a much smaller part of the Permanente Creek basin than do artificial features, they occupy a greater area in the Permanente Creek basin than in the West Fork Permanente Creek basin. In 1984, active natural erosional landforms occupied 34 acres in the Permanente Creek basin in 1984, compared with 12 acres in the West Fork basin (fig. 10). There were more debris slides and small, rapidly eroding watercourses in the Permanente Creek basin (tables 7 and 8). In 1984, a total of 0.13 mile of channel in Permanente Creek basin was adjacent to active natural erosional landforms (all landslides), but there were no active natural erosional landforms adjacent to channels in the West Fork Permanente Creek basin.

Total area covered by artificial erosional landforms in the Permanente Creek basin (table 8) remained almost constant between 1948 and 1968 but nearly doubled between 1968 and 1984. By contrast, the area covered by natural erosional landforms remained constant between 1968 and 1984. The landform categories that increased most in area between 1968 and 1984 were bare ground, spoils piles, and rills. The amount of sediment retained in the downstream flood-control channel managed by the Santa Clara Valley Water District also increased during this period. Although the flood-control channel was constructed in the mid-1950s, sediment removal was not necessary until

TABLE 16.--*Results of synoptic storm sampling in the Permanente Creek basin, 1986*

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; ton/d, tons per day; $(ton/d)/mi^2$, tons per day per square mile; --, no data]

Station No. (fig. 8)	Time (hours)	Streamflow (ft^3/s)	Suspended sediment: Concentration (mg/L)	Suspended sediment: Discharge (ton/d)	Suspended sediment: Yield [$(ton/d)/mi^2$]
			Storm of January 30, 1986		
11166570	1020	--	64	--	--
11166571[1]	1020	--	1,830	--	--
	1030	--	10,500	--	--
11166572	0945	0.54	320	0.47	0.25
11166573	1110	2.34	4,375	27.6	8.4
11166574	1120	2.34	736	4.6	1.4
11166575	0810	3.53	360	3.4	0.89
	1150	3.53	375	3.6	.93
			Storm of January 31, 1986		
11166569	1210	1.77	488	2.2	2.01
11166573	1040	8.12	20,700	454	138
11166574	1045	8.12	10,100	221	67.4
11166575	1008	43.5	11,700	1,370	356
	1320	8.12	2,420	53.1	13.7
			Storm of February 14, 1986		
11166569	0930	12.4	1,460	48.8	40.6
11166571[1]	1030	--	1,140	--	--
11166573	1210	69.3	25,800	4,830	1,460
11166574	1200	69.3	14,600	2,730	828
11166575	0750	44.2	9,330	1,110	288
	0835	64.7	11,900	2,080	539
	1245	--	22,000	--	--
	1600	75.6	11,000	2,250	582

[1]Sampling station is at outfall of culvert draining unpaved road.

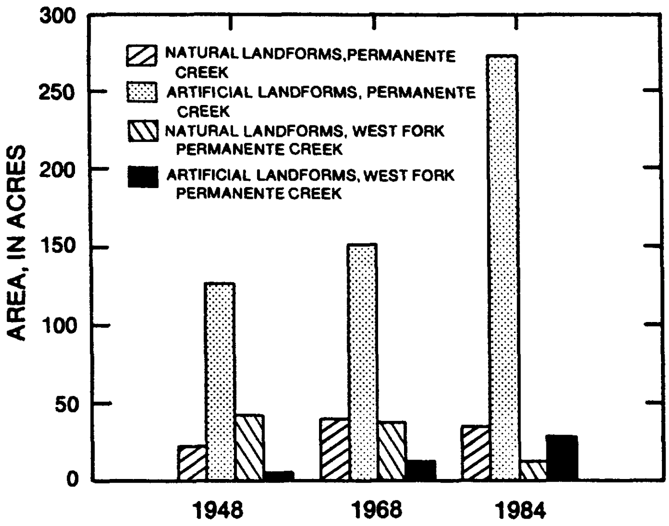

FIGURE 10.– Acres covered by natural and artificial erosional landforms in the Permanente Creek and West Fork Permanente Creek basins in 1948, 1968, and 1984.

1976, when 1,107 yd^3 were removed (Randy Talley, Santa Clara Valley Water District, written commun., 1988). The coincidence of sediment accumulation with large increases in the area covered by bare ground does not, of course, prove direct cause and effect, but it does suggest a relation.

Although no previous studies have specifically investigated changes in sediment transport resulting from limestone quarrying in coastal California, studies in other areas have documented changes in sediment yields due to surface mining and in particular to erosion of spoils piles. Results of these surface-mining studies (table 17) are not directly transferable to the Permanente Creek basin because of major differences in climate, geology, and physiography, but they do illustrate the range of changes in sediment yield which have accompanied surface mining.

All the studies cited in table 17 show large increases in sediment yield following surface-mining operations, and these increases range from about 2 to 300 times the sediment yields of undisturbed land. For example, McCabe (1985) reported that 94 percent of the sediment yield from the Cane Branch basin in Kentucky originated from spoils piles, although spoils occupied only 10 percent of the basin area. Collier (1970) reported that whereas undisturbed areas in the same basin had sediment yields of 20-30 (ton/yr)/mi^2, spoils banks and mining haul roads had sediment yields of 27,000 and 57,600 (ton/yr)/mi^2, respectively. Although the actual production of sediment due to spoils piles and related features in the Permanente Creek basin is unknown, these previous studies indicate that the presence of such features in the Permanente Creek basin and their absence in the West Fork Permanente Creek basin could explain, in part, the large differences in the observed sediment yields of these two basins (table 5). Results from surface mining studies indicate that it would be possible to account for the entire average sediment yield of 4,680 (ton/yr)/mi^2 at station 11166575 based solely on erosion of spoils piles and related features.

Results of Synoptic Sampling

Results of the synoptic sampling for the storms of January 30, January 31, and February 14, 1986 (table 15), indicate that suspended-sediment concentration and discharge increased substantially between sampling points upstream and downstream from the large spoils and storage piles and rilled areas along the main channel of Permanente Creek. Several large, stable landslides are also adjacent to this channel reach. All the samples collected at the upstream stations 11166569 and 11166570 had sediment concentrations much lower than samples collected below the areas of rills and spoils piles associated with the limestone quarry and cement plant (stations 11166573, 11166574, and 11166575). Direct comparison of concentrations at the various sampling points, however, is complicated because samples were collected at different times

TABLE 17.--*Results of previous studies documenting effects of surface mining on sediment yields*

[All results, except those of Ringen and others (1979), were originally given in kilograms per hectare. Results of Ringen and others (1979) were originally given in cubic meters per square kilometer per year and were converted to tons per year per square mile [(ton/yr)/mi²] by assuming a bulk density of 0.047 ton per cubic foot for deposited sediment. mi², square miles; km², square kilometers]

Author and year of study	Description of study site	Sediment yield [(ton/yr)/mi²] Control	Sediment yield [(ton/yr)/mi²] Spoils	Remarks
Collier (1970)	Three headwater basins ranging in size from 0.26 to 0.85 km² (.10 to .33 mi²) in Kentucky	20-30	27,000	
Collier and Musser (1964)[1]	Three headwater basins ranging in size from 0.26 to 0.85 km² (.10 to .33 mi²) in Kentucky	21.4	840	Measured 1957
		28.0	1,930	Measured 1958
Gilley and others (1977)[2]	Bare and topsoil-covered spoils in North Dakota	57.1	5,140	Bare spoils
		57.1	21,100	Topsoil covered
Lusby and Toy (1976)[2]	Rehabilitated spoils at two coal mines in Wyoming	248	528	Mine 1
		6.6	1,730	Mine 2
McCabe (1985)[1]	Three headwater basins ranging in size from 0.26 to 0.85 km² (.10 to .33 mi²) in Kentucky (no mining activity since 1960)	206	1,170	Measured 1974
Ringen and others (1979)[1]	Unrehabilitated coal mine and adjacent rangeland in Wyoming	68.5	794	

[1]Paired or multiple-basin studies comparing small drainage basins impacted by surface mining to basins unaffected or only slightly affected by mining (control basins). Sediment yields for these basins are annual values.
[2]Rainfall-simulation studies on small field plots comparing sediment yields of spoil piles resulting from mining with sediment yields from nearby undisturbed plots (controls).

relative to the storm hydrograph. When data in table 15 are compared with data available for station 11166575, however, it is clear that sediment concentration increases substantially between stations 11166569 and 11166575 during the storm periods included in table 15. At no time during the storms on January 30, January 31, or February 14 did sediment concentrations at station 11166575 drop below concentrations of samples at the upstream stations 11166569 or 11166570. The minimum concentration estimated from the plot of sediment concentration through time at station 11166575 (See Porterfield, 1972) was 202 mg/L on January 30 (between 1000-1500 hours), 2,190 mg/L on January 31 (between 0900-1400 hours) and 6,100 mg/L on February 14 (between 0300-1600 hours). These synoptic data, therefore, indicate large contributions of sediment to the channel between stations 11166570 and 11166573.

Data in table 16 indicate that the settling basin located below the cement plant (fig. 2) was partially effective in reducing sediment discharge. On January 31 and February 14, sharp decreases in suspended-sediment concentration and discharge are evident between stations 11166573 and 11166574, which are located upstream and downstream from the cement-plant settling basin. Concentrations of more than 10,000 mg/L, however, still were measured downstream from the settling basin. Field observations indicated that the settling basin filled with sediment between February 14 and 20, 1986, and was ineffective in retaining sediment during later phases of the wet February-March 1986 period.

Sediment discharge from roads

Inspection of the 1984 aerial photographs indicates that about 12.6 miles of roads in Permanente Creek basin cover about 8.3 acres. Because most of these roads are unpaved and are drained by various kinds of unpaved ditches, they represent a sediment source not considered in the erosional-landforms mapping previously discussed. To demonstrate the potential role that roads play as sediment sources, three samples of road runoff for sediment-concentration analysis were collected at station 11166571. Results of this sampling are shown in table 16. Station 11166571 is at a culvert outfall immediately adjacent to the channel of Permanente Creek. Sediment concentrations in the road samples collected at the culvert ranged from 1,140 mg/L to 10,500 mg/L. Sediment production from road surfaces in the Permanente Creek basin cannot be estimated adequately from the few sediment-concentration data collected from road surfaces. The available data, however, indicate that roads do contribute sediment to channel systems in the Permanente Creek basin, but the extent of the contribution is unknown.

Comparison of Sediment-Transport Curves for the Permanente Creek and West Fork Permanente Creek Basins

The relation between streamflow and sediment discharge is commonly referred to as a sediment-transport curve (Glysson, 1987). This relation is useful because not only can it be used to predict sediment transport for a given water discharge, but when normalized by dividing water and sediment discharge by drainage area, it can be used to compare sediment transport in different streams. Sediment-transport curves for Permanente Creek and West Fork Permanente Creek were combined with results of the rainfall-runoff modeling to estimate the effects of human activity on sediment yields in the Permanente Creek basin. The rainfall-runoff modeling was used to provide a measure of the effects of human activity on runoff. (See section, "Predicted effects of impervious surfaces on runoff."), and the West Fork sediment-transport curves were used to estimate the amount of sediment that would be transported by a given water discharge under natural basin conditions. This estimate, of course, assumes that the West Fork sediment-transport curve provides a reasonable representation of conditions in Permanente Creek prior to quarry operations.

Sediment-transport curves for both Permanente Creek and West Fork Permanente Creek were determined for individual years using mean daily values of water and total sediment discharge determined for stations 11166575 and 11166578. The presence of the two small settling basins upstream from station 11166578 necessitated a modification of the West Fork sediment-transport data. The combined trap efficiencies of these two basins were estimated at 62 percent using methods described by Brune (1953). When comparing sediment discharge on a unit-area basis (tons per square mile), this trapping of sediment must be taken into account, because sediment retained in the basins probably would have been transported past station 11166578 if the settling basins had not been constructed. To develop sediment-transport curves for the West Fork that could be used to estimate sediment discharge for Permanente Creek basin, the drainage area (1.58 mi^2) upstream from the settling basins was reduced by 62 percent, because only 38 percent of the sediment from this area could be expected to pass the gaging station. Thus, net effective drainage area for the West Fork was 2.00 mi^2 [(2.98 mi^2-1.58 mi^2)+(1.58 $mi^2 \times 0.38$)] rather than 2.98 mi^2. Unit sediment discharge used in the sediment-transport curves for the West Fork were calculated by dividing sediment discharge by 2.00 mi^2 rather than by 2.98 mi^2. Water discharge values were divided by 2.98 rather than 2.00 because the settling basins retained little of the streamflow from upstream areas. Sediment-transport curves for Permanente Creek were not adjusted, because (1) the upstream settling basin is small and (2) sediment filled the downstream basin completely between February 14 and 20, 1986.

Sediment-transport curves for moderate and high water discharges for Permanente Creek and West Fork Permanente Creek basins are shown in figure 11. Data used to determine these curves are shown in table 18. As suggested by Glysson (1987), the sediment-transport curves were drawn after considering sediment sources and flow conditions in the two basins. Glysson (1987) reported that several regression equations are generally needed to define completely the sediment-transport curves at a given site and that slopes of the lines for high flows are generally less than slopes for medium flows. Four separate relations were used to represent sediment-transport curves for each basin. As can be seen in figure 11, sediment-transport curves during moderate flows had steeper slopes than those for the highest flow days (5 days in Permanente Creek and 3 days in the West Fork). Sediment-concentration data indicate that these less steep slopes were caused by the depletion of available sediment during high flows, resulting in smaller increases in sediment discharge per unit area increase in water discharge. During our study, this depletion occurred at about 13 $(ft^3/s)/mi^2$ in the West Fork and at about 20 $(ft^3/s)/mi^2$ in Permanente

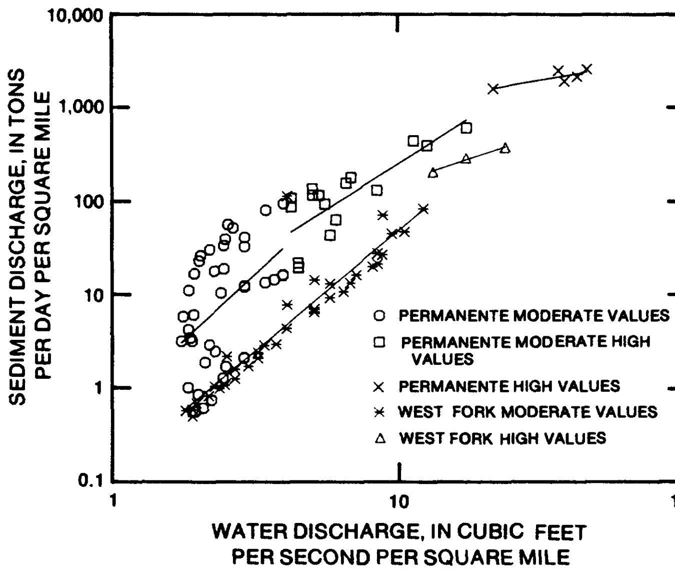

FIGURE 11.– Sediment-transport curves for Permanente Creek and West Fork Permanente Creek. Only data associated with water discharge greater than 1.0 cubic foot per second per square mile are shown. Data points are mean daily values of water and sediment discharge. Lines between points were determined by regression analysis.

Creek. The five high-flow days in Permanente Creek were between February 14 and 19, 1986, and the three high-flow days in the West Fork occurred sequentially between February 17 and 19, 1986.

As analysis of the sediment sources in the two basins indicates, sediment probably is depleted in the West Fork Permanente Creek basin at lower water discharges than in Permanente Creek basin because sediment supply seems to be considerably less in the West Fork basin. The sediment-transport curves for the two streams also indicate that sediment availability may be greater in Permanente Creek than in the West Fork Permanente Creek (Nolan and others, 1986). Slopes of the sediment-transport curves for the two basins are approximately parallel (fig. 11). Transport curves for the two streams differ primarily in the their intercepts: the West Fork relations

TABLE 18.--*Mean daily values of total sediment yield measured during days when mean daily streamflow exceeded 1 cubic foot per second per square mile at the Permanente Creek and West Fork Permanente Creek gaging stations*

[$(ft^3/s)/mi^2$, cubic feet per second per square mile. $(ton/d)/mi^2$, tons per day per square mile]

Date	Streamflow [$(ft^3/s)/mi^2$]	Sediment yield [$(ton/d)/mi^2$]	Date	Streamflow [$(ft^3/s)/mi^2$]	Sediment yield [$(ton/d)/mi^2$]
Permanente Creek near Monta Vista (11166575)					
11-12-84	2.41	32.6	3-11-86	5.95	61.9
11-13-84	2.41	18.4	3-12-86	5.18	113
11-27-84	2.49	54.9	3-13-86	4.92	114
2- 8-85	2.85	31.9	3-14-86	4.14	85.2
3-26-85	2.23	17.4	3-15-86	6.48	154
12- 2-85	1.89	5.96	3-16-86	8.29	128
1-31-86	2.59	50.5	3-17-86	5.70	42.2
2-12-86	2.25	2.41	3-18-86	4.40	21.2
2-14-86	21.2	1,560	3-19-86	4.40	19.2
2-15-86	36.0	2,430	3-20-86	4.40	18.9
2-16-86	17.1	598	3-21-86	3.89	16.1
2-17-86	42.0	2,095	3-22-86	3.89	15.8
2-18-86	37.8	1,873	3-23-86	3.63	14.2
2-19-86	45.3	2,520	3-24-86	3.37	13.2
2-20-86	12.4	387	3-25-86	2.85	12.2
2-21-86	6.74	177	3-26-86	2.85	11.9
2-22-86	4.92	134	3-27-86	2.85	11.9
2-23-86	3.89	93.0	3-28-86	2.46	1.67
2-24-86	3.37	78.8	3-29-86	2.85	2.07
2-25-86	2.85	39.9	3-30-86	2.85	2.05
2-26-86	2.43	38.1	3-31-86	2.41	1.24
2-27-86	2.15	29.5	4- 1-86	2.20	.73
2-28-86	1.96	22.3	4- 2-86	2.05	.60
3- 1-88	1.89	16.3	4- 3-86	1.92	.54
3- 2-86	1.81	10.9	4- 4-86	1.86	3.11
3- 3-86	1.73	5.70	4- 5-86	1.81	4.15
3- 6-86	1.81	.98	4- 6-86	1.84	3.37
3- 7-86	1.99	25.4	4- 7-86	1.97	.83
3- 8-86	5.44	91.71	4- 8-86	2.07	1.84
3- 9-86	4.14	105	4- 9-86	2.15	2.85
3-10-86	11.1	438	4-10-86	1.71	3.11

TABLE 18.--*Mean daily values of total sediment yield measured during days when mean daily streamflow exceeded 1 cubic foot per second per square mile at the Permanente Creek and West Fork Permanente Creek gaging stations*--Continued

Date	Streamflow [$(ft^3/s)/mi^2$]	Sediment yield [$(ton/d)/mi^2$]	Date	Streamflow [$(ft^3/s)/mi^2$]	Sediment yield [$(ton/d)/mi^2$]
West Fork Permanente Creek near Monta Vista (11166578)					
2-14-86	4.03	75.2	3-11-86	5.70	8.62
2-15-86	8.72	46.6	3-12-86	8.39	14.0
2-16-86	5.03	9.40	3-13-86	8.05	13.1
2-17-86	13.1	137	3-14-86	6.38	7.11
2-18-86	17.1	192	3-15-86	8.72	17.5
2-19-86	23.5	250	3-16-86	10.4	31.0
2-20-86	12.1	55.0	3-17-86	6.71	8.79
2-21-86	8.40	18.1	3-18-86	5.70	6.11
2-22-86	7.05	10.7	3-19-86	5.03	4.63
2-23-86	5.03	4.32	3-20-86	4.03	2.87
2-24-86	3.69	1.96	3-21-86	3.36	1.89
2-25-86	3.19	1.38	3-22-86	3.19	1.58
2-26-86	2.65	1.05	3-23-86	2.95	1.13
2-27-88	2.25	.69	3-24-86	2.65	.83
2-28-86	1.88	.38	3-25-86	2.45	.70
3- 1-86	1.88	.33	3-26-86	2.35	.65
3- 8-86	4.03	5.20	3-27-86	2.15	.54
3- 9-86	2.48	1.44	3-28-86	1.95	.45
3-10-86	9.40	29.5	3-29-86	1.78	.38

are generally about an order of magnitude lower than those for Permanente Creek (fig. 11). Nolan and others (1986, p. 4-76) pointed out that the levels of sediment-transport curves are indicative of sediment supply--that is, the greater the availability of sediment, the higher the intercept.

Estimate of Sediment Transport in the Permanente Creek Basin Under Natural Conditions

The effects of cement plant and quarry operations on sediment yields in the Permanente Creek basin were estimated by applying streamflow predicted by PRMS under actual and assumed natural basin conditions to sediment-transport curves for Permanente Creek and the West Fork. Actual hydrologic conditions were those described previously in the section "Rainfall-Runoff Modeling." Natural hydrologic conditions were simulated by replacing the parameters for impervious surfaces in HRU P5 (the location of the cement plant and quarry) with parameters representing natural soil and vegetation. Sediment-transport curves for Permanente Creek were considered representative of present basin conditions, and sediment-transport curves for the West Fork were considered representative of natural conditions, that is, conditions prior to development of the cement plant and quarry. This approach allowed us to distinguish between the effects of basin hydrology, as determined from PRMS simulations with and without impervious areas, and the effects of sediment availability, as determined by the intercepts of the sediment-transport curves (fig. 11), on the sediment yield of the Permanente Creek basin.

The sediment yield of the Permanente Creek basin under natural conditions can be estimated by applying the sediment-transport relation representative of natural conditions (the West Fork curves) to streamflow predicted for natural basin conditions (no impervious areas). The overall effect of the cement-plant and quarry operation can then be estimated by subtracting the estimated natural sediment yield from the measured sediment yield (table 5).

Because runoff per unit of drainage area was higher in Permanente Creek than in West Fork Permanente Creek, the sediment-transport relation for the West Fork had to be extended beyond the range of measured daily sediment discharge to allow the application of the West Fork sediment-transport relation to streamflows predicted for Permanente Creek. The West Fork sediment-transport curve was extended on the basis of the relation for the three highest flow days shown in figure 11. This extension seems to represent the best estimate of the sediment-transport curve at high water discharges, because the sediment supply should continue to be depleted at higher discharges, and thus sediment discharge should increase at a reduced rate (slope). If for some reason the curve did not "flatten" at higher streamflows, as shown in figure 11, the slope of the sediment transport curve would probably remain constant for streamflows ranging from 1.7 to 30.0 $(ft^3/s)/mi^2$.

To provide estimates of the effects of the cement plant and quarry on sediment yields in the Permanente Creek basin, sediment-transport curves were applied to predicted streamflows in four separate combinations. First, sediment yields were estimated for present-day basin conditions by applying the Permanente Creek sediment-transport curves (fig. 11) to streamflow predicted by PRMS under existing conditions, that is, with impervious areas included in HRU P5. These estimates (table 19, column 2) provide a measure of how closely predicted values match measured sediment yields (table 5). The average value, 4,650 ton/mi^2, closely matches the measured yield, 4,680 ton/mi^2.

The second combination consisted of applying the Permanente Creek sediment transport curves to streamflow predicted by PRMS with all impervious surfaces removed and replaced with parameters appropriate for natural soil and vegetation. The resulting sediment yields (table 19, column 3) illustrate the effects of eliminating surface runoff from impervious areas while leaving the sediment supply unchanged from existing conditions. An implicit assumption of this procedure is that removal of the impervious areas would not affect the sediment-transport curve. The impervious areas apparently substantially increase sediment yields during dry years but very little during wet years (table 19, column 3).

TABLE 19.--*Predicted sediment yields at Permanente Creek near Monta Vista (11166575)*

[Sediment yields predicted "with impervious surfaces" use runoff predicted when Precipitation-Runoff Modeling System (PRMS) was run using parameters describing impervious surfaces. Sediment yields predicted "without impervious surfaces" use runoff predicted when PRMS was run after substituting parameters describing natural soil and vegetation for those describing bare impervious surfaces]

[ton/mi^2, tons per square mile]

Water year	Sediment yields predicted using sediment transport curves (ton/mi^2)			
	Station 11166575		Station 11166578	
	With impervious surfaces	Without impervious surfaces	With impervious surfaces	Without impervious surfaces
(1)	(2)	(3)	(4)	(5)
1985	200	80	15.0	7.6
1986	13,725	13,415	3,991	3,918
1987	34	4	4.5	1.2
Average	4,650	4,500	1,340	1,310

For the third combination, sediment yields were predicted by applying the West Fork sediment-transport curve, assumed to represent natural conditions in the Permanente Creek basin, to streamflow predicted by PRMS for existing basin conditions, that is, with impervious areas included in HRU P5. The resulting sediment yields (table 18, column 4) indicate the effects of sediment supply, as determined by the intercepts of the sediment-transport curves for Permanente Creek and the West Fork, because the predicted hydrologic response of the Permanente Creek basin is unchanged from existing conditions. Differences in predicted sediment yields listed in columns 2 and 4 of table 18 are, therefore, entirely due to sediment availability.

Finally, sediment yields were predicted by combining the West Fork sediment-transport curves with streamflow predicted under natural conditions in HRU P5. This combination provides a measure of the effects of both sediment sources and streamflow variations caused by impervious surfaces in HRU P5. Results, shown in table 19, column 5, represent estimated sediment yields from Permanente Creek under natural conditions. Differences between the predicted natural and the measured sediment yields represent the estimated effects of the cement plant and quarry operations on sediment yields in the Permanente Creek basin.

Tables 5 and 19 indicate that under natural conditions, sediment yields from Permanente Creek basin could be about four times higher than yields from the West Fork basin (compare values in table 19, column 5, with values in table 4, column 5) mostly because Permanente Creek basin is more responsive to precipitation than is the West Fork basin. This difference is reflected in the calibration of PRMS and by the higher runoff per square mile in the Permanente Creek basin (table 1). Table 19 also indicates that even after considering differences in runoff characteristics, sediment yields from Permanente Creek basin are still 3.5 times higher than they would be if the main channel transported the same amount of sediment for a given water discharge per unit area as does the West Fork channel (compare values in table 19, column 5, with values in table 5, column 3).

Table 19, column 5, represents the best estimate of what sediment yields in Permanente Creek basin would be under natural conditions. Several assumptions, which have been noted previously, underpin the estimate. First, as noted in the section "Sediment sources," there are probably some differences in sediment sources between Permanente Creek and West Fork Permanente Creek basins, even under natural conditions. Permanente Creek basin has more area covered by natural sediment sources than West Fork Permanente Creek (table 7). Because the preceding analysis uses sediment-transport curves from the West Fork basin as indicators of sediment transport under natural conditions in the Permanente Creek basin, results of the analysis might tend to underestimate natural sediment yields from Permanente Creek basin. Considering the relative amount of land disturbance caused by artificial erosional landforms compared to natural erosional landforms (tables 7 and 8), only a small amount of the differences between sediment yields shown in table 19, column 5, and table 5, column 5, are likely the result of variations in natural erosional landforms in the basins. Second, if for some reason, the West Fork sediment-transport curve did not flatten, the relation between streamflow and sediment discharge would most likely extend past values of 13 $(ft^3/s)/mi^2$ at a slope similar to the one that describes data between 1.7 and 13.0 $(ft^3/s)/mi^2$ (fig. 11). In that case, the predicted yield for Permanente Creek under natural conditions for the 3-year study period would be about 8,600 ton/mi^2, about half the 17,600 ton/mi^2 of sediment measured at station 11166575 and trapped in the settling basin upstream from station 11166575.

CONCLUSIONS

The average sediment yield measured at station 11166575 from the Permanente Creek basin was 14 times greater than the yield from the West Fork basin measured at station 11166578 during 1985-87. After considering sediment trapped in the settling basin 0.5 mile upstream from station 11166575 and that trapped in the two basins upstream from station 11166578, the difference in yields was reduced to 12 times [5,870 $(ton/yr)/mi^2$ compared with 480 $(ton/yr)/mi^2$]. Part of this large disparity in yields results from the higher values of runoff per unit of drainage area in the Permanente Creek basin. Results of rainfall-runoff modeling indicate that the higher runoff in the Permanente Creek basin is caused by natural differences in basin physiography. Although cement-plant and quarry operations have large effects on runoff in Permanente Creek during low and moderate flows, they have little effect during high flows, when most sediment transport occurs.

Although cement-plant and quarry operations seem to have had little effect on runoff, they apparently have had major effects on sediment availability. Of the 307 acres of active erosional landforms mapped on 1984 aerial photographs, 273 acres (89 percent) were composed of artificial features. Not only were these landforms abundant, but many were in areas where sediment delivery to stream channels probably was high. Of the 1.6 miles of main-channel streambanks that were immediately adjacent to artificial landforms, 1.1 miles were adjacent to unconsolidated, steeply sloping spoils piles.

The increased availability of sediment in the Permanente Creek basin is indicated by the relatively high intercepts (levels) of sediment transport curves for that stream. Sediment-transport curves show that streamflow in Permanente Creek carried suspended-sediment loads that were an order of magnitude higher than the loads carried by the same flows in the West Fork, which is comparatively undisturbed by human activities. If sediment-transport curves for the West Fork Permanente Creek basin are similar to what sediment-transport curves would be for Permanente Creek under natural basin conditions, sediment yield in Permanente Creek is about 3.5 times higher than it would be under natural basin conditions. This higher sediment yield seems to result from a large supply of available sediment rather than from higher runoff.

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