# Moss Landing Marine Laboratories

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SAND TRANSPORT STUDIES IN MONTEREY BAY, CALIFORNIA

Annual Report, Part 5, 1973

by

Robert E. Arnal, Eric Dittmer and Evelyn Shumaker

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Moss Landing Marine Laboratories
of the
California State University and Colleges
at
Fresno, Hayward, Sacramento, San Francisco, San Jose, and Stanislaus

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Sea Grant Program

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# I. INTRODUCTION

Background:

In the fall of 1970, a program of baseline studies in Monterey Bay was initiated for the benefit of the communities of the region. The main objective was to provide scientific data that would enable local governments to make better decisions in the long range planning of the Monterey Bay Region. Initial funding was provided by the Office of the National Sea Grant Program and continued for a period of three years. Additional support was provided by AMBAG (Association of Monterey Bay Area Governments) and to a smaller degree by the U.S. Army Corps of Engineers. A Regional Advisory Committee was formed of representatives from regional universities and colleges, elected officials and community leaders to identify studies most useful to local authorities. It is through such meetings that the recreational and economic importance of sand in Monterey Bay was discussed. Consequently, the sand transport studies described below were initiated. *

For practical and financial reasons the area investigated was limited to that shown in Figure 1 as the study area. In addition, the area is a natural geographic unit since the northern and southern boundaries are rocky points around which little sand was thought to be transported. Thus the investigation is limited by Point Santa Cruz on the north, Point Pinos on the south and the 20 fathom contour offshore (Figure 2). The senior author supervised the study; both junior authors were Sea Grant Research Assistants. Eric Dittmer

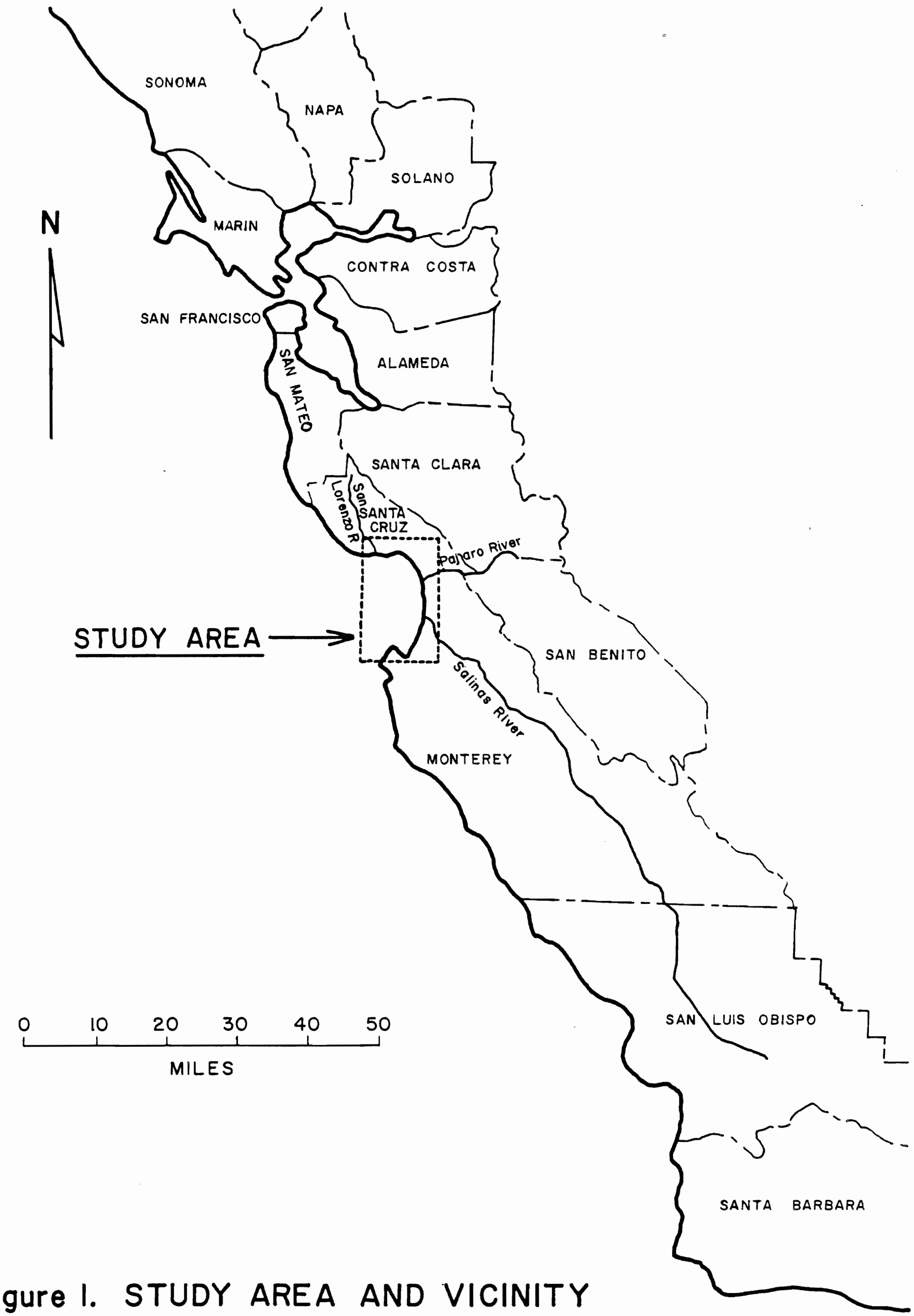



Figure I. STUDY AREA AND VICINITY

summarized in his Master's thesis report the results of the work completed after two years of study (Dittmer 1972).

Previous Studies:

The textural characteristics of the nearshore sediment of Monterey Bay have been investigated in detail in three Master's theses completed in 1968. Wolf (1968) studied the clastic sediments of the entire Monterey Bay in relation to the current patterns of the Bay. Yancey (1968) placed the emphasis on the mineralogical composition of the clastic sediments. He drew his conclusions on sediment transport by examining the changes in composition of the heavy mineral fractions after establishing the most probable provenance. His study, however, is mostly of the northern half of the Bay. Dorman (1968) limited his thorough investigation to the sediments of the southern half of Monterey Bay. Time limitations, however, led the author to make some assumptions that he recognized himself as unwarranted, such as that of a balanced sand budget for southern Monterey Bay.

Eolian action on the beaches of Monterey Bay and the age and origin of the coastal dunes are dealt with in detail in Cooper's Memoir (1967) on the coastal dunes of California. His results and conclusions gave much valuable data for our study. The geology of Monterey Canyon and Monterey Bay is discussed thoroughly in a paper published by Martin and Emery in 1967. More recently, the preliminary results of a seismic reflection survey show the structure of the floor of Monterey Bay (Greene 1970). This author used a grid pattern of profiles one mile apart and at right angles to each other to insure a systematic coverage of Monterey Bay.

California Division of Mines and Geology County Report 5 (Hart 1956) supplied the data for our estimates of sand mining operations. U.S. Army Coastal Engineering Research Center Technical Memorandum No. 19 (Bowen and Inman 1966) provided the procedure and the basic equation for our calculation of volumes of longshore sand transport.

Approach Used:

Three classic processes are considered, namely erosion, transportation and deposition. These processes will be examined successively to determine the components of a preliminary sand budget for Monterey Bay. This budget will be based on a short duration from the geologist's point of view, but one that might be considered long term by the engineer, i.e. 50 to 100 years minimum and up to 3,000 years maximum. We will first consider the process of erosion and the supply of sediment to Monterey Bay, second the process of transportation of sediment, and third the sediment losses and the process of deposition in Monterey Bay to a depth of 20 fathoms. Conclusions and recommendations will be presented at the end of this report.

## ACKNOWLEDGMENTS

We wish to thank the many graduate students who have participated in this study; in particular John Oliver, Peter Slattery and Stephen Pace who provided precise information on sedimentation losses in the head of Monterey Canyon. Thanks go to Gary McDonald who drafted the figures. Thanks also to Dr. Burton Gordon of the Geography Department at San Francisco State University and to Dr. Warren Thompson of the Naval Postgraduate School for making available documents in their possession, especially maps now out of print and wave refraction diagrams. However, the most complete refraction diagrams were those obtained through the courtesy of the San Francisco Office of the U.S. Army Corps of Engineers which saved us hundreds of hours of tedious work; for this we are especially grateful to Robert Sloan, Douglas Pirie, Chris Augen and Richard Ecker. Drs. William Broenkow and Robert Hurley were kind enough to read the manuscript; their editorial comments are appreciated.

## II. EROSION AND THE SUPPLY OF SEDIMENT TO MONTEREY BAY

There are four possible ways in which sediment can be delivered to Monterey Bay. It can be transported alongshore from coastal regions to the north or south. It may be blown in by onshore winds. It may be delivered by rivers both as suspended load and traction load. It may also be eroded by wave action from the coast. The last two ways are somewhat related and inversely important; when rivers deliver abundant sediment, coastal erosion is likely to be stopped or at least decreased. When the river sediment load is decreased, the coast is deprived of the sediment protection from wave attack and coastal erosion will increase. There is, of course, the additional variation due to the irregular occurrence of storm waves seasonally and over

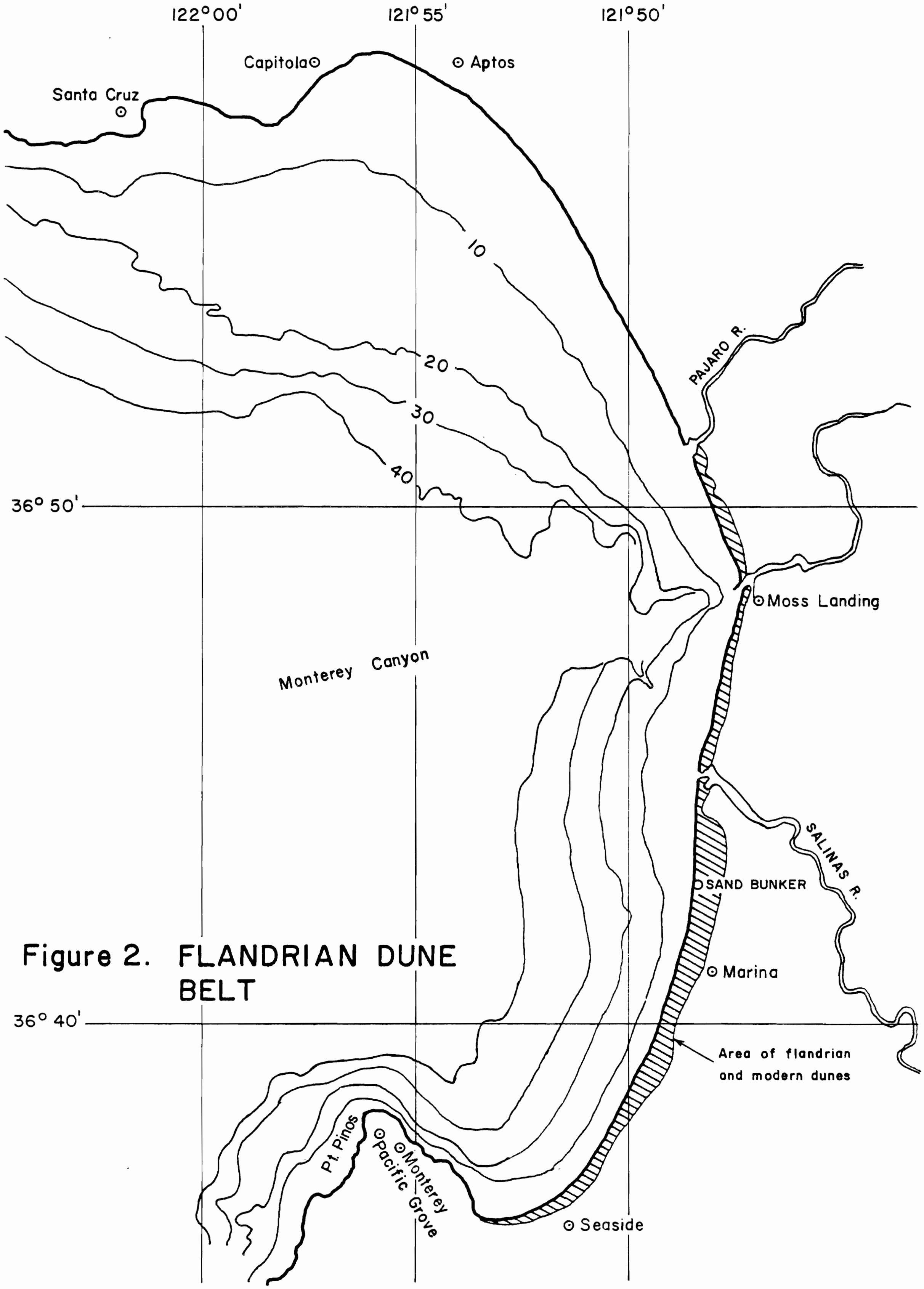



Figure 2. FLANDRIAN DUNE BELT

periods of several years. These have different effects on different parts of the Bay according to the direction of wave approach.

Supply from Outside Monterey Bay Sediment supplied to Monterey Bay includes the input of longshore transport past Santa Cruz Point, the northern boundary, and Point Pinos, the southern boundary. The input from the north is by far the more significant due to the large percentage of waves from the northwest. Wave attack from the same direction would carry unconsolidated material southward from Point Pinos (Figure 2) away from Monterey Bay.

Construction of the Santa Cruz Small Craft Harbor jetty in 1963 allowed the amount of sand, in active transport at that time, to be estimated fairly accurately. Beach surveys before and after construction by the U.S. Army Corps of Engineers (1958, 1969) show that 600,000 cubic yards of sand accumulated on the beach west of the jetty during the two years following completion. During that time, little sand was transported over or around the end of the jetty as the beach was very narrow compared to the length of the jetty. Now, however, sand is easily blown eastward over the top of the jetty by wind. The width of the beach and shallow depth at the end of the jetty also allow substantial amounts of sediment to travel around the tip. In addition, the jetty, built of large concrete tetrapods, is permeable to the passage of sand through, and a large, though undetermined, amount enters the inlet channel. In this manner, some sand finds its way downcoast. However, harbor access is blocked periodically. Nearly 100,000 cubic yards of sand were removed from the channel alone in May 1972.

In contrast, there is no evidence of sand transport around Point Pinos, the southern boundary of the Bay. Hence the total sand input to Monterey Bay from outside is estimated at 300,000 cubic yards per year, all of it entering from the north.

Supply from Offshore Winds A second possible source is that of sand being blown offshore into nearshore waters of Monterey Bay by offshorewinds. Cooper, who is credited with much experience in dune studies (Cooper 1958, 1967) noted that only winds with velocities of 16 miles per hour and over are effective in moving sand. Offshore winds are not common in the Monterey Bay region. Because of the orientation of the shoreline south of Moss Landing, only wind directions from 030° to 210° (NNE to SSW) can be considered offshore wind directions. Data presented in the Pacific Gas and Electric Company Project Report 73-650 (PG&E 1973, Tables 9 and 10) show that offshore winds as defined above represent 32% of all wind occurences and that 25% of winds with velocities of 16 miles per hour and over blow toward the ocean. The resulting effect of all winds capable of moving sand is to blow back into the ocean one out of every four cubic yards of sand blown in in the formation of littoral dunes. In Section IV, under "Losses by Deflation," we show that 30,000 to 50,000 cubic yards of sand are lost annually from the beach to the littoral dunes. This amount is small compared to volumes moved by other processes, such as longshore transport; hence the volume of sand blown to sea by winds, representing only a quarter of the deflation losses, is considered unimportant since it would amount annually to 10,000 cubic yards on the average.

Supply from Rivers Several approaches may be used to arrive at an estimate of the volume of sand delivered to Monterey Bay by rivers. Stream flow data from the water resources division of the USGS may be used. Another estimate may be obtained from the sediment yield per square mile of the drainage basin of the rivers and a third estimate may be derived from the determination of river loads in relation to annual precipitation.

a) Stream flow

Hamlin (1904) published data giving the monthly water discharge for the Salinas River from July 1900 to June 1901. Summation of these numbers indicates a total annual water discharge for that period of 796,798 acre-feet. Assuming only one gram of sand per kilogram of water, the total amount of sediment delivered to the Bay that year would be 1,285,500 cubic yards. Of the 796,000 acre-feet of water discharge, 676,000 acre-feet or 85% were delivered during three winter months. Hence this must have been high velocity flow during which water is capable of carrying a large quantity of sand in suspension load and traction load. Other data (U.S. Geological Survey 1971) indicate that about 96,000 acre-feet per year are now removed for irrigation and municipal use above Spreckles, California, where the U.S. Geological Survey maintains the last downstream gauging station on the Salinas River bed. The flow of the river has been regulated partly by the Nacimiento Reservoir beginning in February 1957 and partly by the San Antonio Reservoir beginning in December 1965.

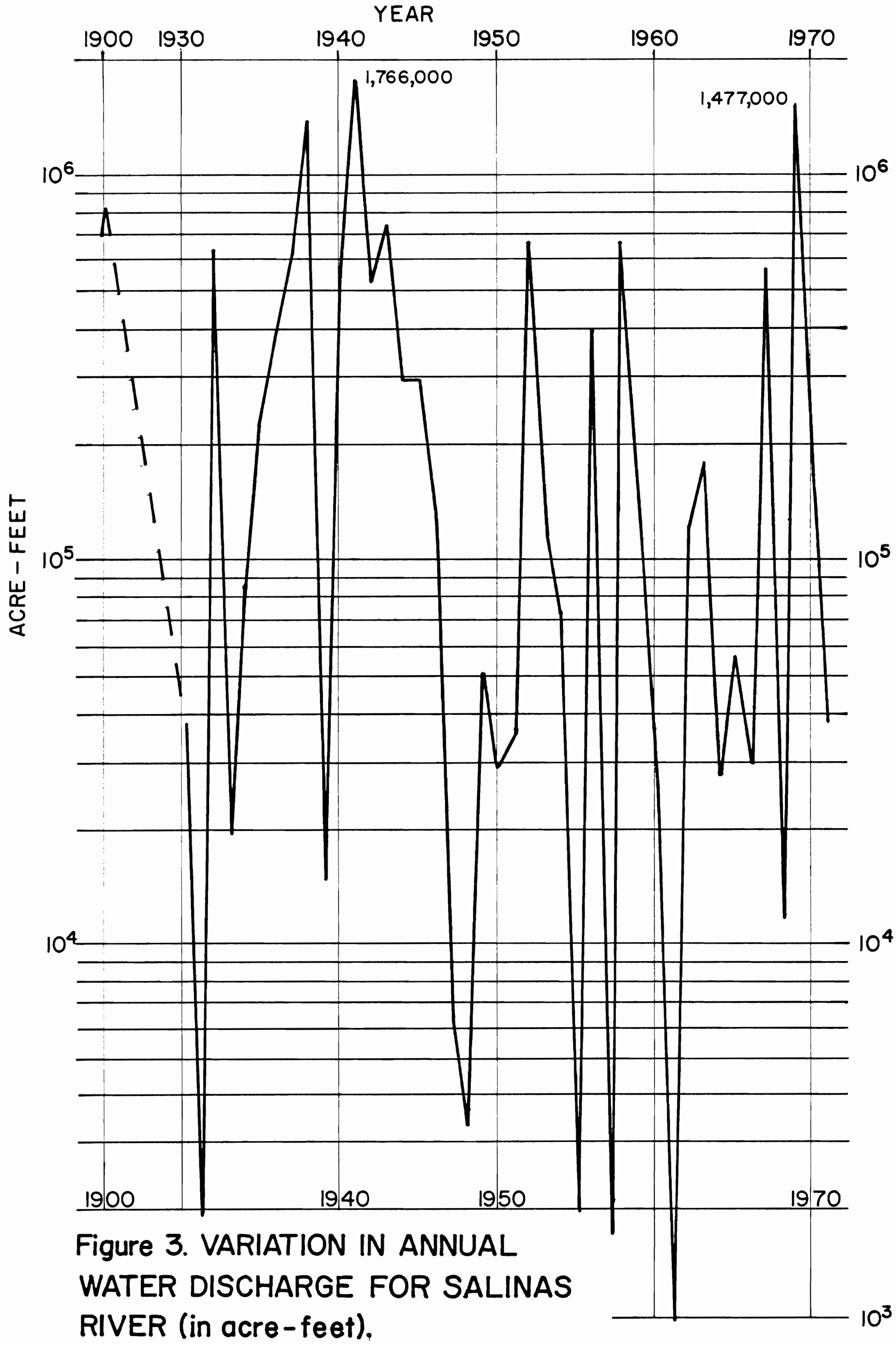



Figure 3. VARIATION IN ANNUAL WATER DISCHARGE FOR SALINAS RIVER (in acre-feet).

Figure 3 and Appendix Table I show that the water discharge of the Salinas River varies enormously from year to year. At Spreckles, California, the discharge for the year 1969 was nearly 1500 times that for the year 1961. Hence, when making calculations to determine sediment volumes, a period of three years such as 1964-67 (Dorman 1968) is clearly insufficient. The sum of the discharge for those three years, 111, 590 acre-feet, is less than one-third of the average annual discharge of 349,611 acre-feet for the 26 year period 1931 to 1956, before construction of the reservoirs. Using such a short period gives results in error by more than a factor of 10.

In the first half of this century, especially when irrigation was minimal, the annual discharge of the Salinas River was more than 100,000 acre-feet greater than it is today; accordingly, the sediment volume delivered to the ocean was higher. After construction of the reservoirs, the flow of the Salinas River has been regulated. This, in addition to obviously large climatic fluctuations, has diminished runoff and has markedly reduced the discharge of the Salinas River. The annual discharge has averaged only 231,000 acre-feet for the last 15 years, in spite of a one and a half million acre-feet flood in 1969. Incidentally, it is estimated (USGS 1971) that the 1969 flood delivered more than 14 million cubic yards of sediment to Monterey Bay.

Thus, for the early part of this century, the Salinas River discharge was about 350,000 acre-feet per year, whereas in recent years this figure has been reduced to a yearly average of 231,000 acre-feet.

The pre-1957 total discharge for all rivers flowing into Monterey

TABLE I

ANNUAL WATER AND SEDIMENT DISCHARGE FOR MONTEREY BAY STREAMS
Data from USGS (1971)

| River | No. years for calculating average | Water Discharge in acre-ft. | Drainage area in sq. miles | Discharge of sand in cu. yds. for 1 g/liter |
|---|---|---|---|---|
| Salinas River at Spreckles average to 1956 | 26 | 349,611 | 4,156 | 564,000 |
| Salinas River at Spreckles 1957 to date | (15) | (231,372) | (4,156) | (373,000) |
| Pajaro River at Chittenden to 1970 | 31 | 110,100 | 1,186 | 178,000 |
| Soquel Creek at Soquel to 1970 | 19 | 23,600 | 40 | 53,000 |
| Aptos Creek at Aptos to 1970 | 12 | 6,060 | 12 | 10,000 |
| San Lorenzo River at Big Trees | 34 | 99,980 | 111 | 161,000 |
| Totals | | 589,351 | 5,505 | 966,000 |
| Totals in round figures | | 600,000 | 5,500 | 1,000,000 |

Bay was about 600,000 acre-feet per year (Table I). Arnal (1961) estimated the sedimentary contribution of the Colorado River and local streams to the Salton Basin, using a figure of one gram of sand per liter of water based on statistical evidence. Climatic conditions in general are similar for the Salinas River drainage basin and the lower course of the Colorado River. However, since the Salinas River is smaller, there is a greater turbulence in the stream bed and the load per unit volume would be greater. Hence the figure of one gram of sand per liter is of the right order of magnitude and most probably conservative. The total annual sand discharge, using the same figure of one gram per liter (or 0.1%) for all streams flowing into Monterey Bay, would amount to approximately 1,000,000 cubic yards (Table I, last column). A summary of water and sand discharges for all important streams of Monterey Bay is given in Table I.

b) Sediment yield per square mile

Johnson (1959) estimated the sand yields of the Santa Maria and Santa Inez Rivers. Both are similar in size to the rivers emptying into Monterey Bay and flow a little south of the study area in a geographic region having almost identical climatic conditions. Hence the sediment yields are comparable. Johnson's figures indicate a yield of 700 cubic yards per year per square mile of drainage basin for the Santa Inez River above the last gauging station, over an area of 820 square miles. For the Santa Maria River the yield is smaller, about 100 cubic yards per year per square mile for an area of 1,800 square miles. By comparison the drainage basin for the Salinas River covers an area of 4,156 square miles but contains a large amount of cultivated acreage which gives a larger sediment yield per square mile; hence a similar but slightly higher figure, 150 cubic yards per square mile, is used for the Salinas River, and 300 cubic yards for the other rivers. Using these values, the calculated sand yield would be 623,400 cubic yards for the Salinas River, and 405,000 cubic yards for the other rivers, giving a total of 1,028,400 cubic yards for all rivers debouching to Monterey Bay. This value is similar to that obtained by the preceding method.

c) River load in relation to precipitation

Langbein and Schumm (1958) studied the sediment yields of river drainage basins of different sizes in relation to mean annual precipitation based on observations at gauging stations scattered over a wide range of climatic conditions. Their first figure showing the relationship between annual precipitation and runoff gives a value of over two inches of runoff for 16 to 20 inches of average precipitation in the drainage area. By comparison, the average rainfall for Santa Cruz is 24 inches, Pajaro 18 inches, Salinas 14 inches, and Monterey 17 inches. Using the value of 2.0 inches of runoff for 16 to 20 inches of precipitation, we calculated a total of 590,000 acre-feet per year for all rivers flowing into Monterey Bay, for a drainage area of 5,505 square miles (Table I). The result is almost identical with the total obtained from stream flow data and shown on Table I, column 2.

A second figure of Langbein and Schumm shows an annual sediment yield of 600 to 800 tons per square mile in function of an effective precipitation of eight to 18 inches per year. Taking the lower figure, 600 tons per square mile, and using 60 pounds per cubic foot of sediment (Langbein and Schumm 1958) gives a volume of 4,000,000 cubic yards of sediment delivered to Monterey Bay. Approximately 70% represents suspended fines that are carried by currents beyond the 20 fathom contour depth, and the remaining 30%, or about 1,200,000 cubic yards, represents the sandy sediment yield in agreement with the two previous estimates.

In summary, total annual sand volumes delivered by streams to Monterey Bay in the pre-1957 period probably varied between 1.0 and 1.2 million cubic yards, whereas in more recent years, it is close to 800,000 cubic yards per year.

Supply from Coastal Erosion There is evidence that coastal erosion has taken place in Monterey Bay for a period of at least fifty years and probably much more. Dittmer (1972) presents evidence of coastal erosion based on cliff recession in northern Monterey Bay. Cliffs averaging 100 feet in height are found between Santa Cruz and Seacliff Beach. The U.S. Army Corps of Engineers (1969) estimates that coastal erosion occurs there at the rate of one foot per year, or approximately 100,000 cubic yards per year, for five miles of exposed cliffs.

Cooper (1967) cites as evidence of coastal erosion the extreme narrowing of the Flandrian dune belt that accumulated during the past 3,000 to 5,000 years opposite Fort Ord (Figure 2) in an area where the maximum height of the dunes would imply a much broader belt. He feels the increase in concavity of the shoreline due to coastal erosion "has resulted in cutting the belt almost in two." Slow retreat of the bluff underlying the central part of the Flandrian dune belt is continuing as shown by the truncated end of sand parabolas on the bay side. Cooper gives also evidence of the rate of erosion with the example of "an atmometric installation placed 2 meters from the edge of the bluff in 1919 and gone over the brink four years later." This yields an erosion rate of about 1.5 to 2 feet per year for the period 1919 to 1923 in the central part of southern Monterey Bay.

In 1971 the State Legislature requested the California Department of Navigation and Ocean Development to conduct a study on the feasibility of constructing a groin to develop a public beach area at Sand City in Monterey Bay, and at the same time, to evaluate the stability of the shoreline at the site. Figure 4 (from DNOD 1972) shows the variation of the position of the shoreline at twelve occasions during a period of nearly thirty years. On April 7, 1944, as determined from aerial photographs, the position of the shoreline is approximately in average position from extreme variations during the five year period 1941 to 1946. Between April 7, 1944 and May 24, 1961, there was a recession of 50 feet over a period of 17 years, an average of three feet per year. Between May 24, 1961 and April 10, 1967, the recession was 30 feet over a period of six years, or five feet per year. Hence it appears that the average annual recession of the shoreline has accelerated progressively from 1.5 to two feet in the twenties

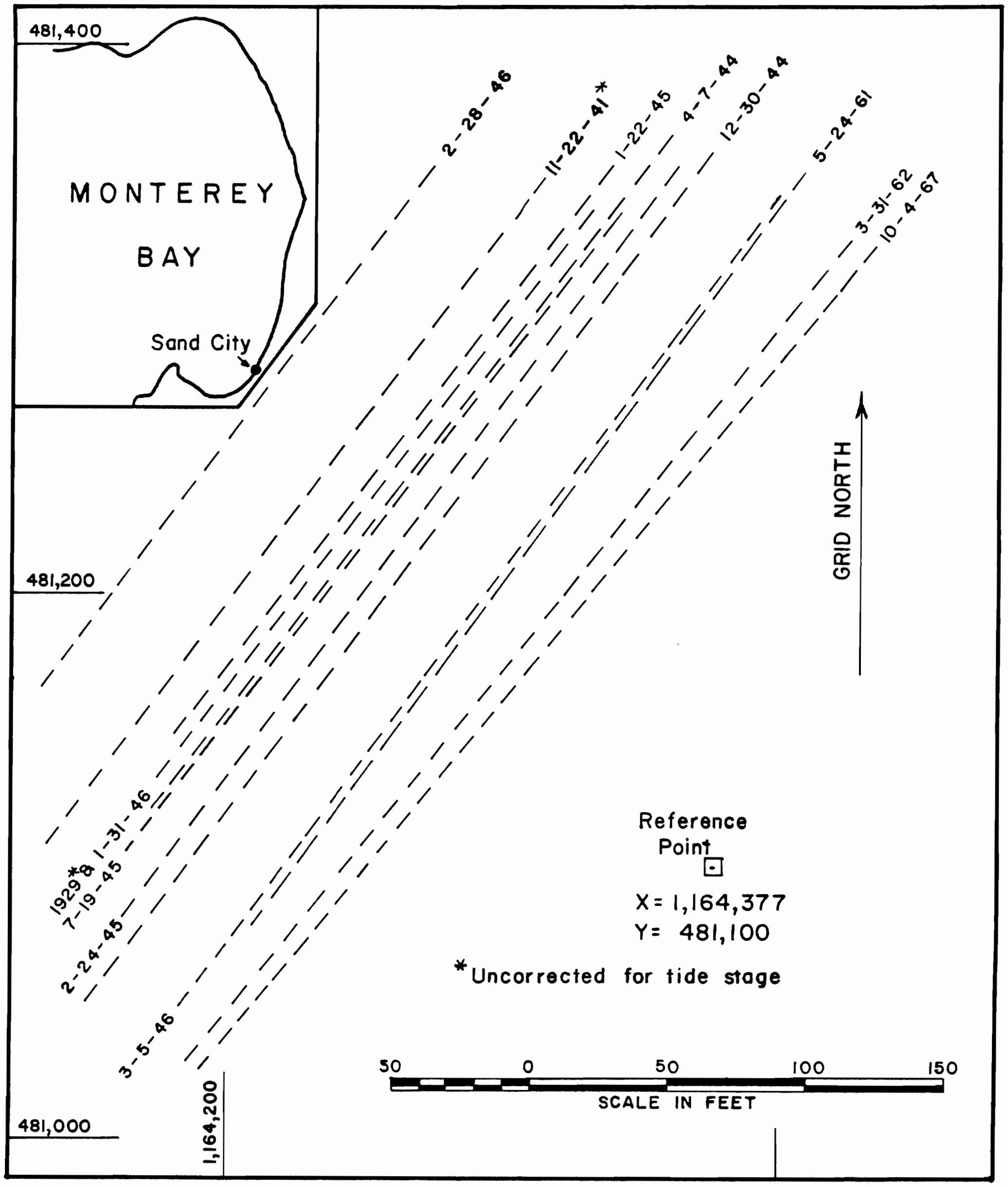



Figure 4. POSITIONS OF SHORELINE OF A PORTION OF MONTEREY BAY. (FROM DNOD, 1972).

(Cooper 1967) to three feet in the fifties, to five feet in the sixties (DNOD 1972). The length of shoreline subjected to coastal erosion between the Salinas River mouth and Monterey is over 13,000 yards, and the average height of the dunes in that area is 22 yards. The volume of sand removed per year has therefore increased from 300,000 cubic yards for the period 1944 to 1961 to 500,000 cubic yards for the period 1961 to 1967. This correlates well with changes in runoff since construction of the dams on the Salinas River.

The total volume of sand supplied to the Bay per year by coastal erosion now exceeds 600,000 cubic yards. Table II below shows a total sand supply to Monterey Bay of 1.8 to 2.0 million cubic yards per year.

TABLE II

SUMMARY OF SEDIMENT SUPPLY TO MONTEREY BAY

| Source | Volume in 1000 $yd.^3/yr.$ | % of Total Supply |
|---|---|---|
| Outside Bay | 300 | 15 - 17 |
| Onshore Winds | Negligible | Less than 0.5% |
| Rivers | 1000 to 1200 | 55 - 60 |
| Coastal Erosion | 500 | 25 - 28 |
| Total | 1800 to 2000 | 100 |

## III. SEDIMENT TRANSPORT

The preceding section discussed the different sources of sediment delivered to Monterey Bay and estimated the annual volume brought to the system from each source. In this section the distribution of the sediment received from the different sources is analyzed in order to learn the location of the areas where losses are most likely to occur.

Processes Several processes are active in transporting sediment both parallel to the shoreline and perpendicular to the shoreline.

Transport of sediment along the shore has been recognized, observed and calculated by many investigators. Inman and his collaborators have given general accounts of effects on the shoreline (Inman and Brush 1973, Bowen and Inman 1966). Longshore transport takes place indirectly as a result of the stress exerted by winds on the sea surface; this stress generates waves. Very little of the energy in the waves is lost during their travel toward the coast. When the waves reach shallow water, their energy is dissipated in part by friction on the bottom with ensuing turbulent motion. Some of the energy is used to put sand particles in suspension in the surf zone. Part of the energy is dissipated by wave refraction. Energy is also used in creating rip currents. Finally, some energy is trapped along the shore, often resulting in an offshore return flow near the bottom.

When waves travel toward the shore, the wave fronts often make an angle $\alpha$ with the direction of the shoreline. The waves refract and become breakers forming a different angle $\alpha_b$ with the beach.

## Figure 5. NEARSHORE CIRCULATION

(adapted from Bowen and Inman, 1966)

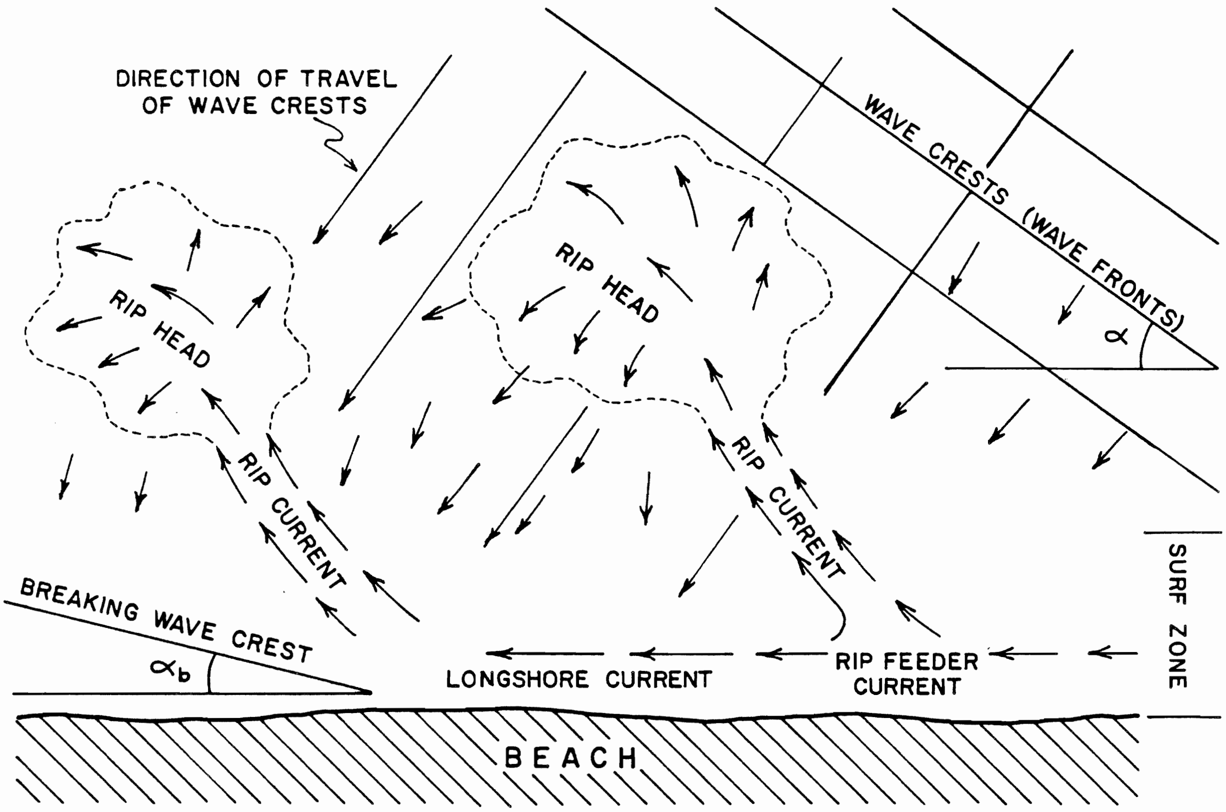
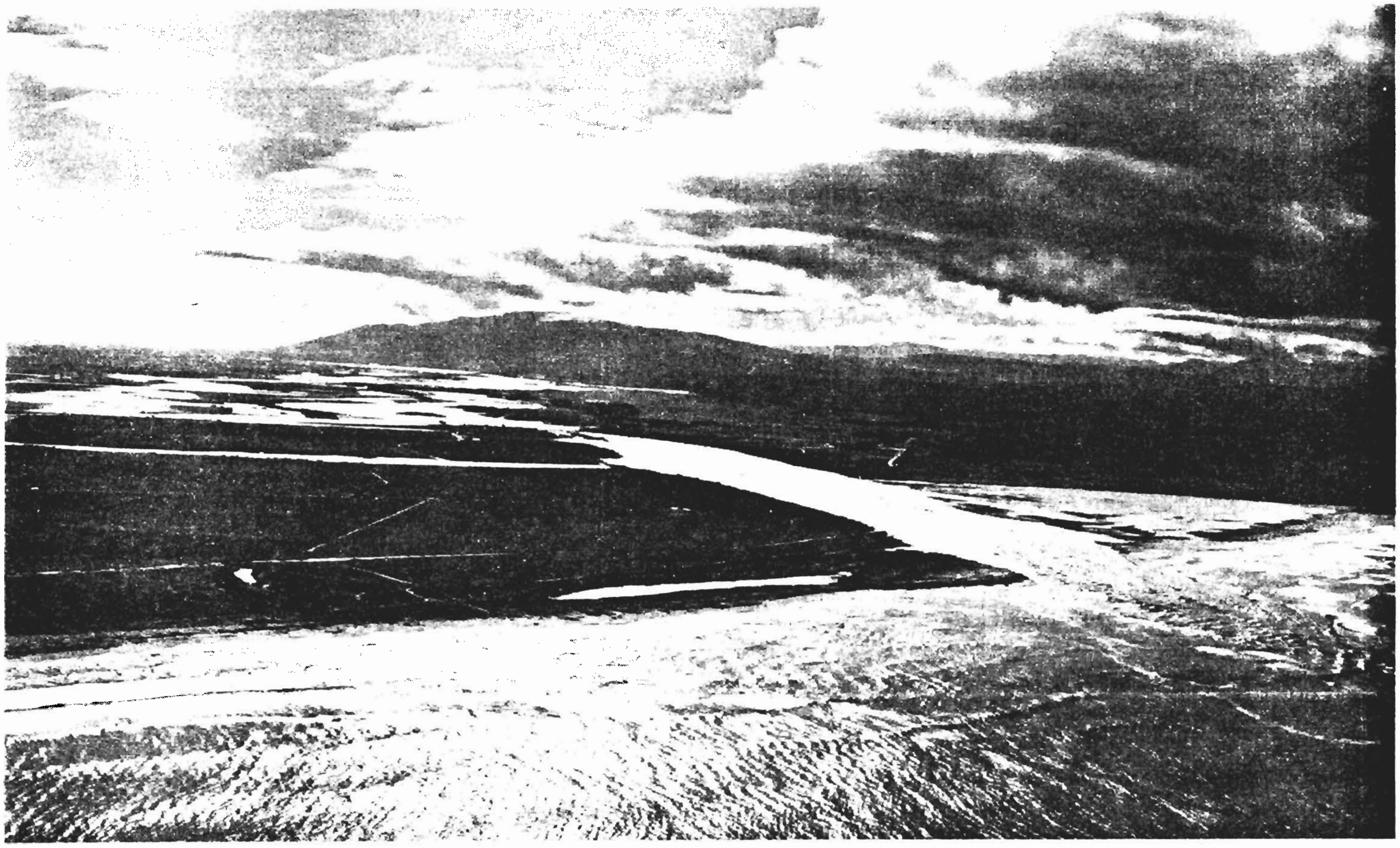


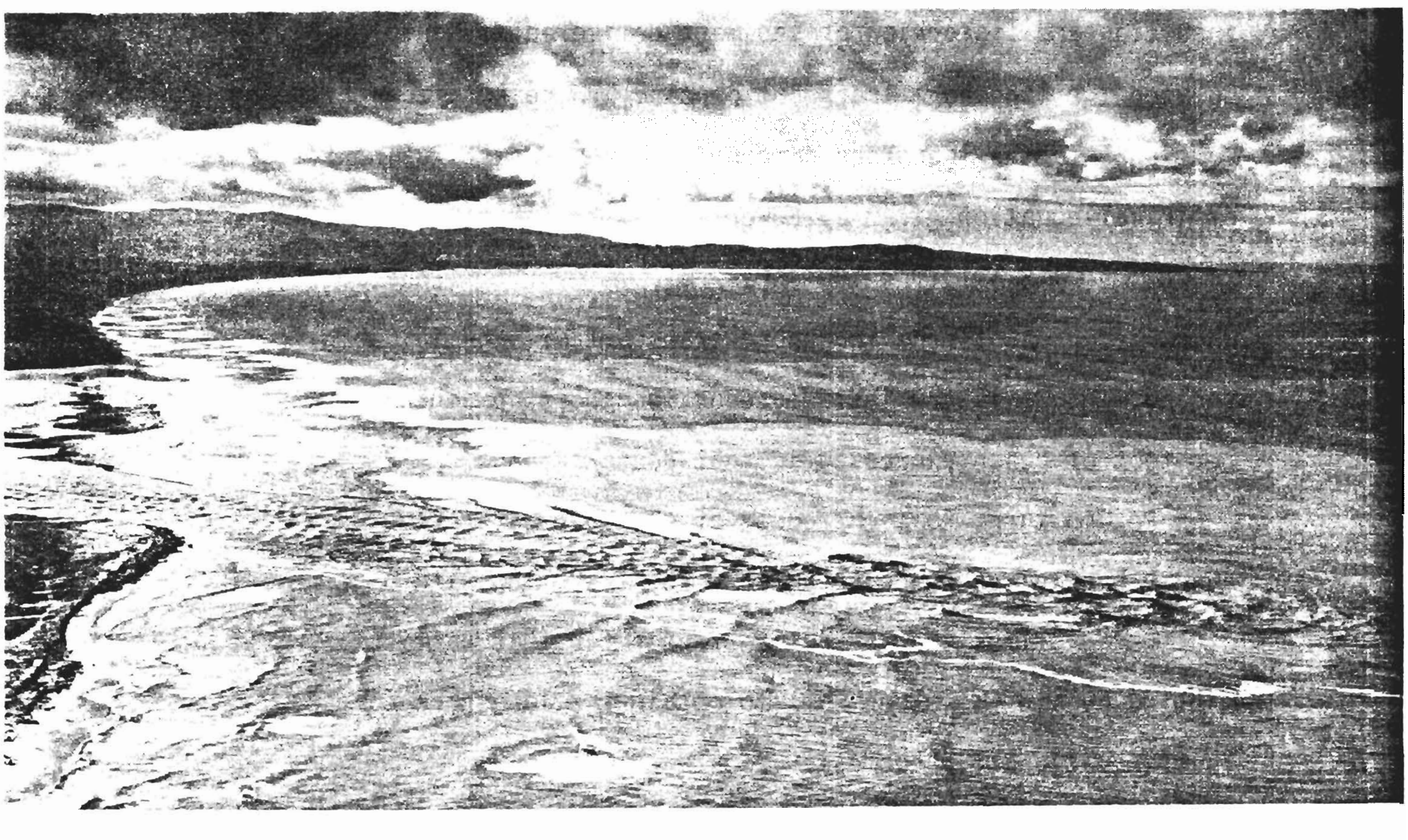

FIGURE 6 (opposite page) -- Photographs of the Salinas River Mouth.

Upper photograph shows the extent of flooding during the 1969 discharge of one and one half million acre-feet of water. Coastal Highway No. 1 was closed to traffic for a few days.

Lower photograph shows high velocity flow from river with large sediment discharge and water discoloration, distance from mouth to right of photograph is over one mile. The point on upper right of photograph is Point Pinos, about 10 miles from river mouth.

Both Photographs, courtesy U.S. Army Corps of Engineers, San Francisco, and Dr. Burton Gordon, San Francisco State University.





This angle is important in calculating the longshore component of wave energy. Figure 5 shows the nearshore circulation in a diagramatic fashion. The area from one rip current to the next is known as a circulation cell. The spacing and the position of rip currents along the shore depends on the angle $\alpha_b$ and on wave height. Transport of water and sediment is shown by the direction of longshore currents along which primary mixing occurs. The width of the mixing zone is that between the outer edge of the rip head and the shoreline. Secondary mixing takes place between the heads of rip currents (Inman and Brush 1973).

In addition to rip currents, there is transport of sediment perpendicular to the shoreline off the river mouths at the time of river discharge. For Monterey Bay this is limited to a four to five month period in the winter. Figure 6 shows that transport of sand in suspension at time of flood may occur several thousand yards offshore. Sand may then be deposited directly in water deeper than 100 feet from both the Pajaro and Salinas Rivers and deeper than 60 feet from Soquel Creek and the San Lorenzo River (personal communications with divers at the Moss Landing Marine Laboratories). Particles of fine silt and clay sizes are more often than not deposited beyond Monterey Bay and are not, as stated (Shepard and Dill 1966) a very important factor at present for deposition in Monterey Submarine Canyon. The reasons for this are:

1) These particles have a slow settling velocity and therefore remain in suspension for several hours to several days.


FIGURE 7 -- Satellite Photographs of Monterey Bay and Vicinity, 1/22/73. Note turbid water from the Salinas River flowing northward and away from submarine canyon area.

2) These particles are delivered in suspension only at the time of river discharge in the winter.

3) When these particles are delivered in greatest quantity, the currents in the Bay are fairly fast (10 to 50 cm/second) and they flow in a northerly direction (Davidson period) and away from the geographic position of the submarine canyon.

Figure 7 is a composite of two satellite photographs taken on January 22, 1973, and is strong evidence in support of the statements above. It also shows that fine particles originating from the Salinas and Pajaro River discharges are still in suspension several tens of miles away from their source.

Longshore Transport Calculations In order to evaluate the distribution and dispersion of sediment delivered to Monterey Bay, we calculated the longshore transport of sand in the surf zone as being proportional to the longshore component of wave power, using the semi-empirical equation given by Bowen and Inman (1966):

$$S = 1.13 \times 10^{-4}\ Pe \qquad \text{(Equation 1)}$$

where S represents the longshore transport of sand in cubic feet per second, and Pe is the instantaneous longshore component of wave power per foot of beach expressed in foot-pound second$^{-3}$.

Pe, in turn, is the product of the deep water progressive wave evergy per unit surface area for waves traveling with a group velocity of $\frac{1/2\ g\ T}{2\pi}$ times the refraction factor for that particular wave, multiplied by $\sin \alpha_b \cos \alpha_b$ to obtain the longshore component only. Thus, Equation (1) becomes:

$$S = \frac{1.13}{10,000} \times \frac{1}{8} \rho g H_o^2 \times \frac{1}{2} \frac{gT}{2\pi} \frac{b_o}{b_b} \sin \alpha_b \cos \alpha_b \qquad \text{(Equation 2)}$$

The following are needed for calculation of longshore sand transport S at any locality along the shoreline: $\rho$ = sea water density in pounds per cubic foot; g = acceleration of gravity in feet per square second; $H_o$ = deep water progressive wave height in feet; T = progressive wave period in seconds; $\frac{b_o}{b_b}$ = the refraction factor (the ratio of a unit length of wave crest in deep water, $b_o$ to what the length has become, $b_b$, at the time the wave breaks); and $\alpha_b$ = the angle between the direction of wave front in the breaker zone and the direction of the shoreline (Figure 5).

Pooling the above constants, the sand transport equation (2) becomes:

$$S = 7.44 \times 10^{-2} H_o^2 T \frac{b_o}{b_b} \sin \alpha_b \cos \alpha_b \qquad \text{(Equation 3)}$$

where $H_o$ is expressed in feet, T in seconds and S in cubic feet per second.

This equation permits us to calculate the amount of sand transport for a wave of known height and period at any locality of Monterey Bay after the refraction factor $\frac{b_o}{b_b}$ and the refraction angle $\alpha_b$ have been determined for each wave characterized by $H_o$ and T.

We selected 10 localities for the entire Bay (Figure 8), five for the northern half and five for the southern half. Station numbers indicate the approximate distance in miles north and south of the entrance to Moss Landing Harbor. After selecting the position of the localities to be used for calculating the sand transport volume and the significant directions and periods for wave approach, it appeared desirable to express our results of sand transport in cubic yards per year in order to

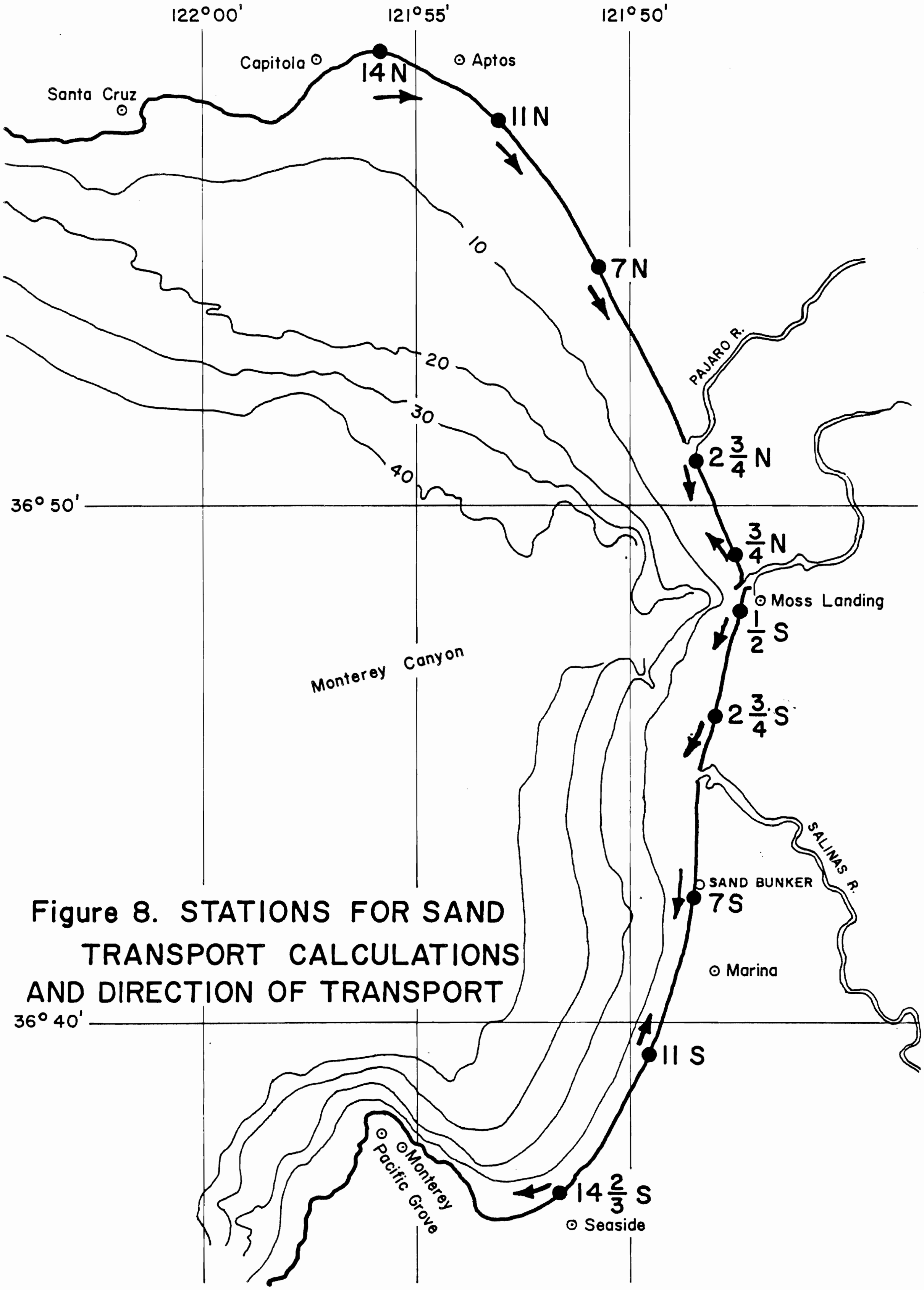



Figure 8. STATIONS FOR SAND TRANSPORT CALCULATIONS AND DIRECTION OF TRANSPORT

be consistent with values used in other sections of this report. Therefore, the summations of the wave height squared were used, and the frequencies of occurrence expressed in per cent computed for the annual volume of sand transport. Thus, Equation (3) becomes:

$$S = 870 \sum (H_o^2 f)\ T \frac{b_o}{b_b} \sin \alpha_b \cos \alpha_b \qquad \text{(Equation 4)}$$

where $\sum (H_o^2 f)$ is the summation of the square of the wave height times the frequency of occurrence for a given wave period. We used the National Marine Consultants (1960) wave statistic data from their Station #3 for all directions except southwest, for which their Station #4 was more appropriate. The total longshore sediment transport was determined for periods of 6 to 8 seconds, 8 to 10 seconds, 10 to 12 seconds, 12 to 14 seconds, and 14 to 16 seconds and directions northwest, west northwest, west, west southwest and southwest (Table III) for the ten stations shown on Figure 8. The term $\frac{b_o}{b_b} \sin\alpha_b \cos \alpha_b$ was obtained for each wave direction and station location from graphic determinations using wave refraction diagrams from the San Francisco office of the U.S. Army Corps of Engineers, the Naval Postgraduate School and those prepared by the senior author. All diagrams used were spot-checked for errors; none were found.

Results of the calculations are shown in Table IV, as well as the direction of sand transport for the ten localities selected for calculations. The direction of sand transport is also shown for each station on Figure 8.

<u>Conclusions</u> Longshore and sand transport in the north Bay increases from 200,000 cubic yards per year east of Santa Cruz to nearly

TABLE III

WAVE REFRACTION DIAGRAMS AND $\sum (H_o^2 f)$
USED FOR SAND TRANSPORT CALCULATIONS

| Direction | Period | $\sum(H_o^2 f)$ | Direction | Period | $\sum(H_o^2 f)$ |
|---|---|---|---|---|---|
| NW | 6 | 355.2 | WNW | 6 | 80.9 |
| NW | 8 | 790.2 | WNW | 8 | 233.0 |
| NW | 10 | 387.6 | WNW | 10 | 287.8 |
| NW | 12 | 202.3 | WNW | 12 | 184.8 |
| NW | 14 | 84.2 | WNW | 14 | 90.2 |
| | | | WNW | 16 | 42.2 |
| W | 6 | 49.8 | WSW | 6 | 21.7 |
| W | 8 | 186.6 | WSW | 8 | 64.2 |
| W | 10 | 270.4 | WSW | 10 | 56.8 |
| W | 12 | 186.3 | WSW | 12 | 36.4 |
| W | 14 | 74.2 | | | |
| SW | 6 | 14.04 | | | |
| SW | 8 | 21.84 | | | |
| SW | 10 | 7.00 | | | |
| SW | 12 | 0.88 | | | |

TABLE IV

VOLUME OF SAND TRANSPORTED AT 10 STATIONS IN MONTEREY BAY

| Stations | Volume in cu. yds./year | Direction of transport |
|---|---|---|
| 14 N | 208,000 | South Downcoast |
| 11 N | 316,000 | South Downcoast |
| 7 N | 444,000 | South Downcoast |
| 2-3/4 N | 572,000 | South Downcoast |
| 3/4 N | 117,000 | North Upcoast |
| Moss Landing | | |
| 1/2 S | 640,000 | South Downcoast |
| 2-3/4 S | 942,000 | South Downcoast |
| 7 S | 616,000 | South Downcoast |
| 11 S | 191,000 | North Upcoast |
| 14-2/3 S | 236,000 | South Downcoast |

600,000 at the mouth of the Pajaro River, which is near a convergence of longshore transport. Near the head of Monterey Submarine Canyon at Moss Landing, there is a divergence in longshore transport which is southerly south of the harbor entrance and northerly north of the harbor entrance. In the south Bay, maximum downcoast transport occurs near the mouth of the Salinas River. There appears to be a convergence with offshore transportation near Marina, at the point where bathymetric contours show changes in direction due to the Salinas River delta (Figure 8).

All sand transport volumes given on Table III are possibly in error by as much as 25% because small errors in reading angles may produce large changes in the longshore components and because irregularities in the direction of the shoreline introduce additional angle errors. The numbers given should be considered merely orders of magnitude.

## IV. DEPOSITION AND SEDIMENT LOSSES IN MONTEREY BAY

Shelf Deposition The quantity of sand moved toward and away from the shoreline may be estimated fairly precisely by determining changes in level over a number of years. This was obtained by measuring the change in area within a bathymetric contour, adding the areas within two successive bathymetric contours and the shoreline, and multiplying by half the contour interval. The method is the same as that used for calculating the volume of sand dunes, but in this instance bathymetric contours are used instead of topographic contours. Planimetric measurements of the areal changes between the shoreline and the 3, 10 and 20 fathom bathymetric contours were made successively for surveys in 1910 and 1948-1950. The charts used were the 1911 and 1956 editions of Coast and Geodetic Survey Chart #5403 at the scale of 1 to 50,000. For the 1911 chart, corrections were applied because of shrinkage over a period of more than 60 years; however, the shrinkage was carefully measured and proved to be uniform over the chart. The corrections were made by multiplying any area measured by a constant.

Each measurement with the planimeter was repeated three times and the four numbers obtained were averaged. The results demonstrated good reproducibility; differences in readings were always less than 0.05 square inches. Since the readings always amounted to two square inches or more, the results have a possible error from planimeter measurements of ± 2%. Hence differences in volume smaller than 2% can be neglected as they may be due to instrumental errors.

Survey dates for early charts of the California coast have been determined since they are important in establishing the duration for volume changes and consequently the annual rates of sediment deliveries.

We have established that there was a resurvey of Monterey Bay made in 1910 by the United States Coast and Geodetic Survey modifying the original survey of 1856 made by the same agency (U.S. Army Corps of Engineers 1958). We obtained boat sheets of the original survey of 1856 at the scale of 1/10000 and compared several hundred points of the original survey with corresponding points on the 1911 chart. We found many new data points and features on the 1911 chart that were obviously the results of the resurvey. These new data points and changes are especially noticeable near the mouth of the Salinas River and around Moss Landing, as should be expected. Checking all these points convinced us of the validity of the 1911 chart as representing conditions prevalent at that time and not a mere duplication of earlier surveys.

Comparison of the same bathymetric contours on the 1911 and 1956 editions of the USC&GS Chart #5403 shows important differences for the three fathom and ten fathom contours and smaller or no apparent changes for the 20 fathom contours. Hence we show the conclusion that most of the deposition of nearshore sands has taken place in Monterey Bay at depths shallower than 120 feet in the four areas in Figure 9. No changes were observed west of 121°55' W longitude either north or south of Monterey Canyon. These areas were not included in the planimetric measurements.

The largest sediment volume changes, over 80 million cubic yards, occurred in Area 1 (Table V) to the west of the mouth of the Salinas River. In Area 2, all changes are 2 per cent or less and should be disregarded as they are within the range of instrumental errors. Thus the total volume changes for the southern half of Monterey Bay amount to 80 million cubic yards, or an annual average of 2,000,000 cubic yards during the period 1910 to 1950.

Sediment volume changes are smaller in the northern half of Monterey Bay. In Area 3, off the mouth of the Pajaro River, volume

TABLE V

VOLUME CHANGES DUE TO OFFSHORE DEPOSITION
BETWEEN 1910 AND 1950 FOR FOUR AREAS SHOWN ON FIGURE 9
In Thousands of Cubic Yards

| Volume Between: | 1910 Survey | 1948-50 Survey | Change |
|---|---|---|---|
| | | AREA 1 | |
| 20-10 fathoms | 689,000 | 728,600 | + 39,600 = 5.7% |
| 10- 3 fathoms | 181,600 | 217,700 | + 36,100 = 19.9% |
| 3- 0 fathoms | 13,700 | 18,500 | + 4,800 = 35.0% |
| | | Total: | + 80,500 |
| | | AREA 2 | |
| 20-10 fathoms | 352,000 | 357,800 | + 5,800 = 1.6% |
| 10- 3 fathoms | 104,500 | 104,900 | + 400 = 0.3% |
| 3- 0 fathoms | 10,000 | 10,200 | + 200 = 2.0% |
| | | Total: | + 6,400 |
| | | AREA 3 | |
| 20-10 fathoms | 363,600 | 371,500 | + 7,900 = 2.2% |
| 10- 3 fathoms | 133,400 | 139,200 | + 5,800 = 4.3% |
| 3- 0 fathoms | 13,700 | 13,300 | - 400 =- 3.0% |
| | | Total: | + 13,300 |
| | | AREA 4 | |
| 20-10 fathoms | 1,197,100 | 1,208,500 | + 11,400 = 0.9% |
| 10- 3 fathoms | 305,800 | 318,100 | + 12,300 = 4.0% |
| 3- 0 fathoms | 12,600 | 14,400 | + 1,800 = 14,3% |
| | | Total: | + 25,500 |

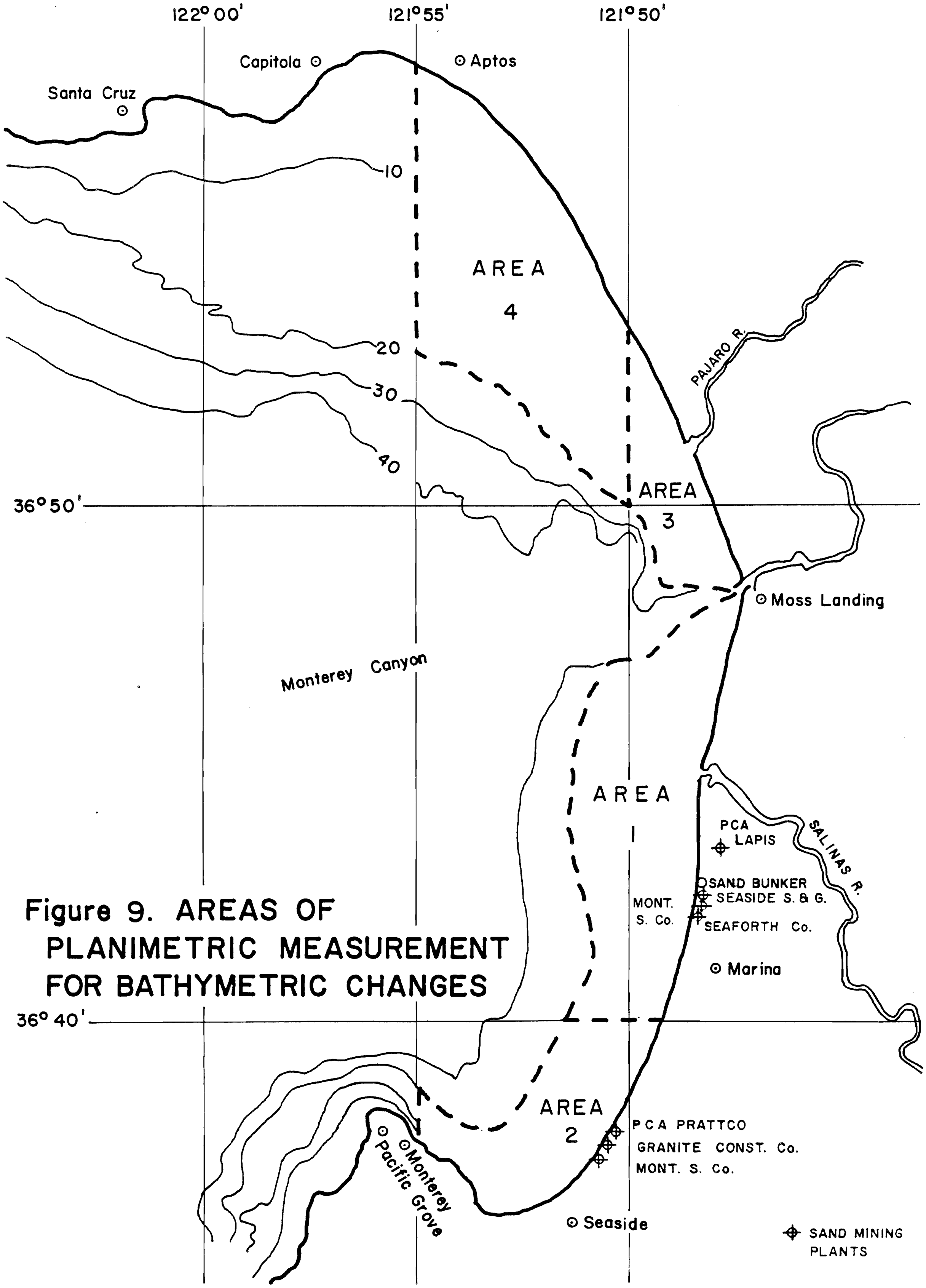


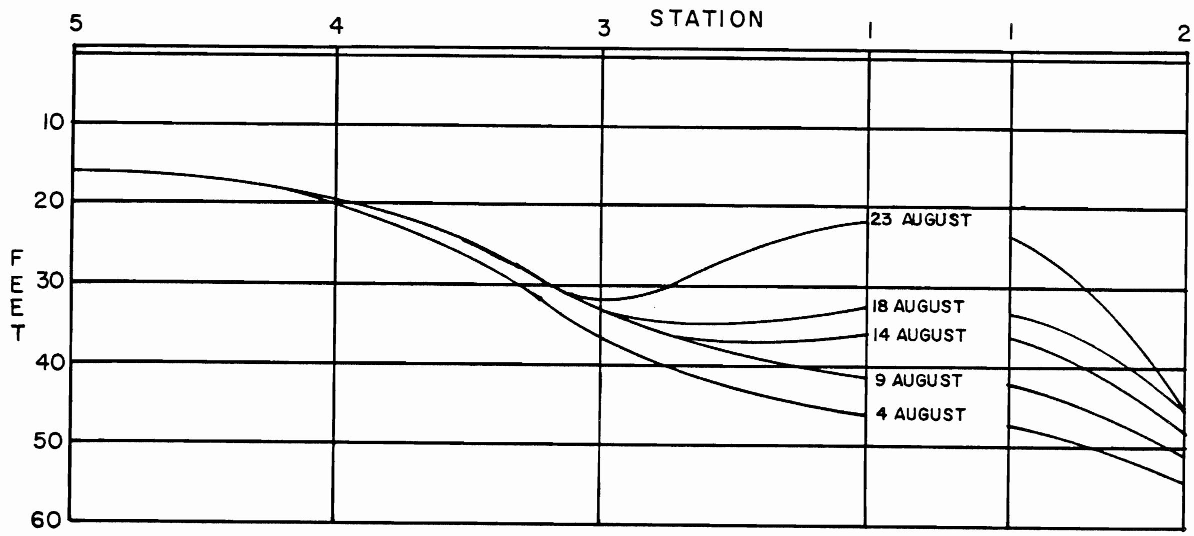

Figure 9. AREAS OF PLANIMETRIC MEASUREMENT FOR BATHYMETRIC CHANGES

changes amounted to 13,300,000 cubic yards. For Area 4, the 20 fathom contour is assumed to be the same for both charts because the 1910 survey does not provide enough data points to precisely trace the 20 fathom contour between 121°55' and 121°50'W longitude. Volume changes for that area are limited to the zone between 0 and 10 fathoms and amount to 14,100,000 cubic yards. Thus the total sediment volume changes for the northern half of Monterey Bay are 27,400,000 cubic yards, or an annual average of 685,000 cubic yards during the period 1910 to 1950.

Downcanyon Sediment Transport This type of sediment loss is the most difficult to evaluate in a sediment budget because very few direct or indirect measurements have been made. Hence the following account of divers' observations during the past six years is especially noteworthy. Shepard and Dill (1966) described three branches at the head of Monterey Canyon: the jetty branch, the middle branch and the southern branch. The following account took place at the southern branch, which is the seaward continuation of the pier at Moss Landing (Figure 10). The southern and middle branch join in about 30 fathoms of water. Beyond that depth, there are only two branches, the jetty branch, which is the direct continuation of the entrance to Elkhorn Slough, and the southern branch.

Between August 4 and August 23, 1967, soundings and visual observations of the bottom topography were conducted by divers at the end of the pier at Moss Landing Harbor. About 27,000 cubic yards of dredge spoil were disposed of by means of a pipe dredge in nearly ten fathoms of water during the two week period. Below is a diagram of the changes that took place along the pier and beyond as the spoil was deposited.

Station 5 is nearest to shore and Station 1 is away from shore. The portion of diagram from Station 1 to Station 2 is parallel to shore but according to divers' reports represents well the shape of the mound over 180° of azimuth. Between Stations 1 and 5 the distance is 210 feet, and between 1 and 2 the distance is 50 feet (Figure 10).




Accumulation of the dredge spoil mound from August 4 to 23, 1967.

Upon completion of the dredging, the mound had been built up some 23 feet from the original bottom profile. It remained in the same shape until October 12, the date of the first winter storm which was of moderate intensity. The main effect of that storm was to flatten, between Stations 4 and 1, the profile of the mound which stood as shown on the diagram until early December. On December 8, 1967, a major storm effected a drastic change in the profile with filling taking place at Station 3 and little or no change at the other stations. A second major storm occurred in mid-January, 1968, and by the end of the month the bottom profile had returned almost to pre-dredging conditions.

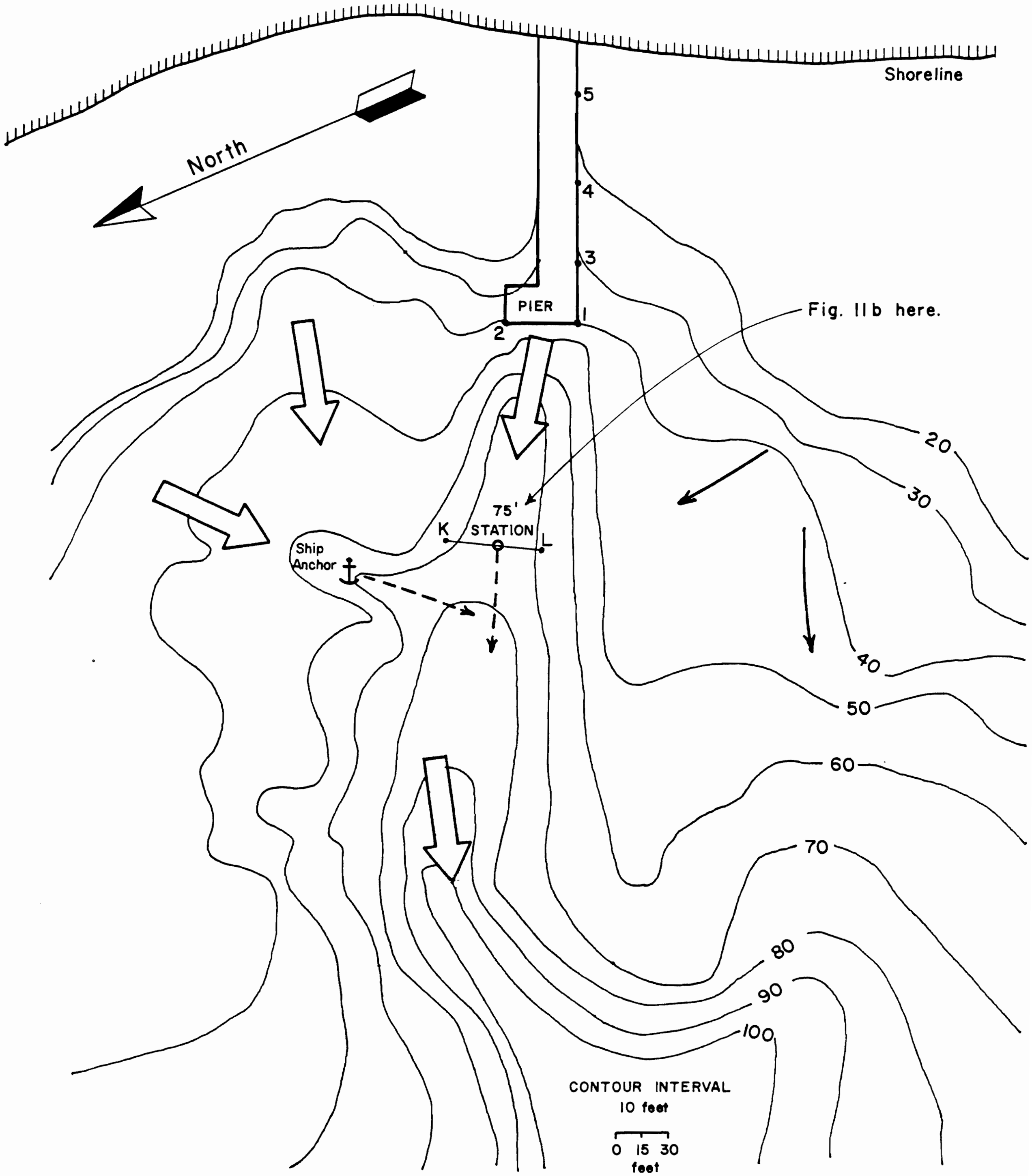
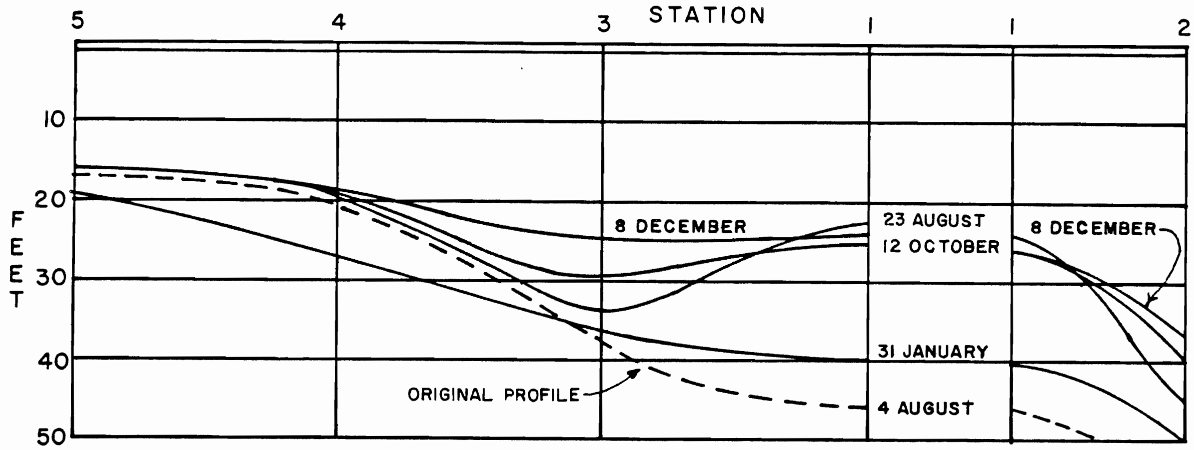



Figure 10. MAP OF HEAD OF MONTEREY SUBMARINE CANYON SHOWING CREEPING AND SLUMPING MOVEMENT OBSERVED BY DIVERS.
(Modified from Oliver and Slattery, 1973).




Dispersion of the dredge spoil mound from 23 August to 31 January, 1968.

In other words, it took more than three months and three winter storms to move 27,000 cubic yards of sand downcanyon.

In order to see how effective Monterey Canyon was in preventing sand transport across the head, fluorescent tagging experiments were conducted both at high tide and low tide near the jetty branch of the canyon head. This area was chosen because the entrance channel to the harbor, which is the direct continuation of the jetty branch (Figure 11A), is maintained at a depth of 15 to 20 feet below mean lower low water. Therefore, the area is the most likely to act as a barrier. Dittmer (1972) reported on these experiments. One was conducted in late winter on March 7, 1972, at low tide. One thousand pounds of green fluorescent sand were placed north of the Moss Landing Harbor north jetty in the swash zone. Twenty-four hours (two tidal cycles) later, fluorescent grains were found at several points north and south of the Moss Landing pier. Another similar experiment was made in late spring on June 7, 1972, at high tide with one thousand pounds of fluorescent sand dumped in the water at the same location.

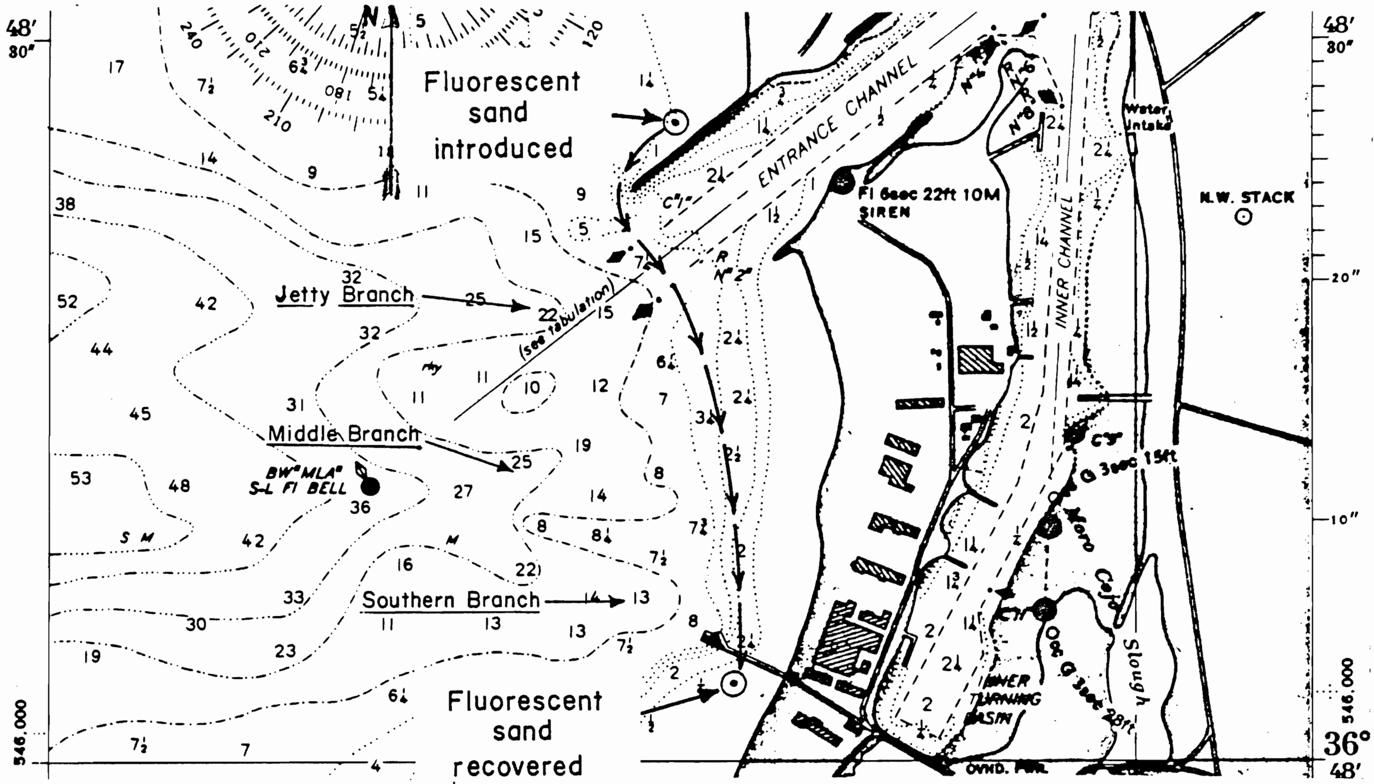
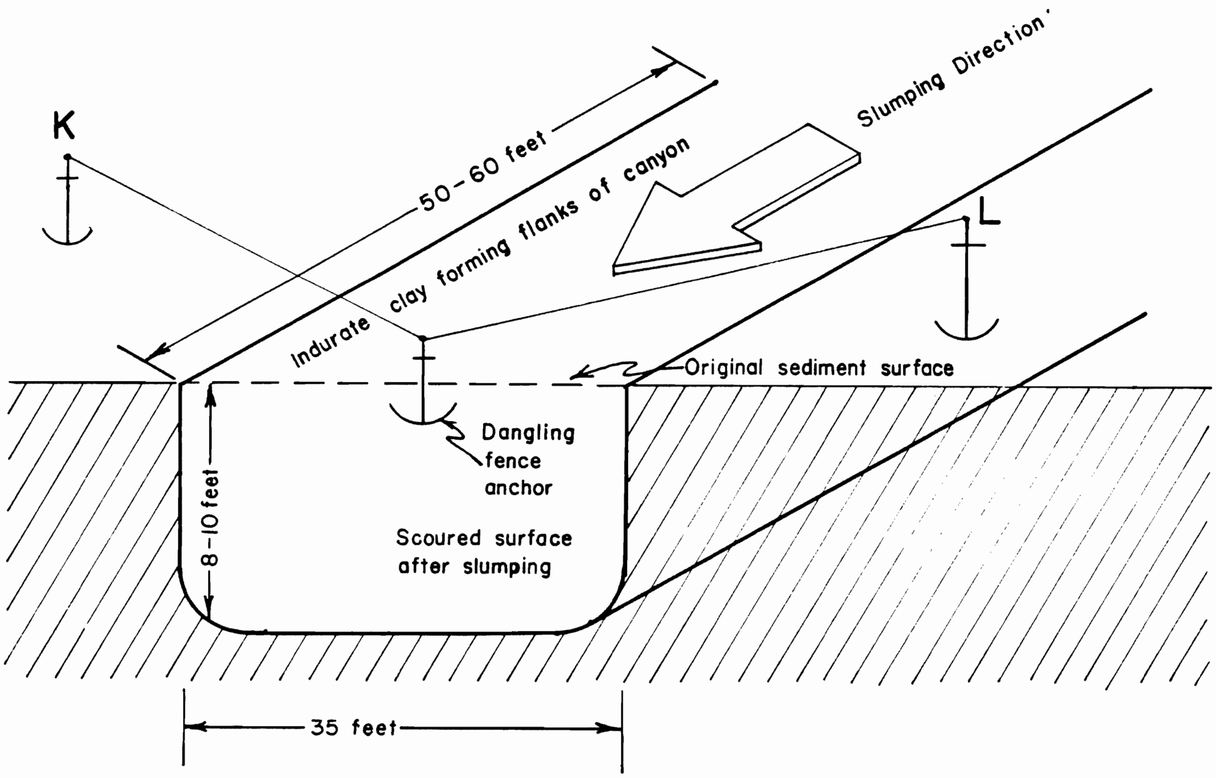



FIGURE 11. A. (above) Sediment Transport Across Moss Landing Harbor Entrance Channel.

B. (below) Detail of Slumping or Mass Movement Observed by Divers in Spring 1973.



In that experiment, bottom samples were taken with a Peterson Grab, beginning one hour after sediment introduction. Sampling was begun at the turning basin in the harbor and proceeded out to the canyon axis to 20 fathoms. The zone of sediment transport across the channel (Figure 11A) was limited to the vicinity of the port and starboard buoys located near the ends of the north and south jetties respectively. Along the beach, fluorescent sand grains were recovered in a zone extending more than 1000 feet both to the north and south of the Moss Landing pier. Repeated sampling in the jetty branch axis of the canyon head beyond the buoys failed to show any fluorescent grains. No doubt some sediment is transported downcanyon; however, the tagging experiment seems to indicate that the transport is mostly alongshore, even across the entrance channel to the harbor.

In the summer of 1971 the Moss Landing dredge spoil project was initiated to study the effects of dredge spoil disposal on the local bathymetry, water quality and benthic and littoral life. The report on this study has been completed (Oliver and Slattery 1973). As a component of that study, the dispersal of the sediment spoil was investigated by fluorescent tagging. More than 10,000 pounds of red fluorescent-dyed sand were deposited with the sandy dredge spoil to determine the dispersion of the material. One hundred pounds were inserted on each of 101 barge loads. The barge loads were dumped in the canyon near the Moss Landing pier (Figure 10) in 60 to 100 feet of water through the summer and early fall. The winter was extremely mild. Repeated sampling downcanyon and on the beach, as well as diver grab sampling at the disposal site, gave negative results until March 7, 1972, some four to five months after the end of disposal operations. On that date, scattered red grains were recovered on the beach near the pier. Microscope examination verified the presence of the tagged sand, although some of the fluorescent paint was faded due to abrasion. Afterwards, sampling on the beach or night surveys with a fluorescent light revealed tagged sand grains in an area extending from the south jetty to a point 400 yards south of the pier. In that instance, it took over half a year for the dispersal of the 90,000 cubic yards of spoil, and no evidence was obtained of downcanyon transport as stated earlier. A point to remember, however, is that a substantial amount was available for downcanyon transport accumulated under rather unstable conditions, and the evidence shows there has been wide dispersal shoreward. Judging from the next experiment, probably less than half of the 90,000 cubic yards of dredge spoil, some 40,000, was carried directly downcanyon. The transport must have taken place over a five month period because of the late start of the winter storms.

Another experiment provides additional data on downcanyon sediment transport. In late spring 1972, divers installed permanent transect lines in the area shown in Figure 11B. This area is an enlarged map of the southern branch of the head of the canyon. The key points of the transect lines were marked by eight-foot fence anchors firmly driven into the sediment (Points K and L, Figures 10 and 11B). At the 75-foot station five two-foot fence anchors were arranged in a direction at right angles to the axis of the canyon across the 35-foot width from one wall to the other. Oliver and Slattery (1973) report that in the fall of 1972 the surface sand slumped away from the pier and water depths near the end of the pier changed from 20 to 25 feet to 35 to 40 feet in the fall and early winter. Further downcanyon at depths of 50 to 60 feet, three moving large sand steps, each about 50 feet long and two to three feet high, were observed. The motion appeared to be more of a creeping nature rather than that of a slump. Rapidly decomposing algae were incorporated with the sediment. These algae, when collected with a grab sampler, were found to be very slippery and somewhat gelatinous to the touch, producing a strong odor of hydrogen sulfide when placed in a sample jar. They apparently act as a lubricant for sediment movement.

By spring of 1973, divers observed that the slumping or sand-creep motion had continued to deeper water. The original sediment surface (Figure 11B) had been lowered eight to 10 feet. The indurated silty-clay walls of the canyon had been swept clean of sand over a distance of 50 to 60 feet along the axis of the canyon and over the 35-foot width of the channel, leaving the fence anchors dangling over the canyon. This took place over a period of three to four weeks between observation dives (Stephen Pace, personal communication). Additional evidence came from the movement of a 500 pound ship anchor from a side channel (70 feet) to the main axis (80 feet) as shown in Figure 10. From this experiment we obtain the volume of sand that went downcanyon as a result of the slump, which amounts to 800 cubic yards over a month for one branch of the canyon. Even if we assume such a slump occurs once a month in each of the three branches of the canyon for six winter months, we obtain a grand total of 15,000 cubic yards per year moving downcanyon. This supports our previous statement that downcanyon transport of sediment funneled through the head of the canyon probably does not amount to more than 40,000 cubic yards per year. This is a small quantity compared to the annual amount of sand delivered to Monterey Bay.

Losses by Deflation These losses represent the amount of sand withdrawn from the budget by wind action. When the wind blows toward the shore at velocities greater than 16 miles per hour, eolian transport of sand occurs. The particles are removed from the beach and accumulate in sand deposits known as the coastal or littoral dunes. Cooper (1967) made an extensive study of the coastal dunes of California and gave special attention to the "Monterey dune complex." He recognizes older dunes which are completely stabilized and extending several miles inland; these he called the pre-Flandrian dunes. They are covered with vegetation, including pine forests, and are bordered along the coast by a zone of younger dunes extending on the average 3,000 feet inland and reaching elevations in excess of 140 feet. These dunes, named the Flandrian dunes, are recognized along the entire California coast. Cooper was able to approximately date the base of the Flandrian dunes at Ano Nuevo just a few miles to the north of Monterey Bay. Due to this close proximity, the age of the Flandrian dunes along the Monterey Bay coastline is assumed to be the same. The radiocarbon dating gives an age of 3,000 to 5,000 years for the base of the Flandrian dunes.

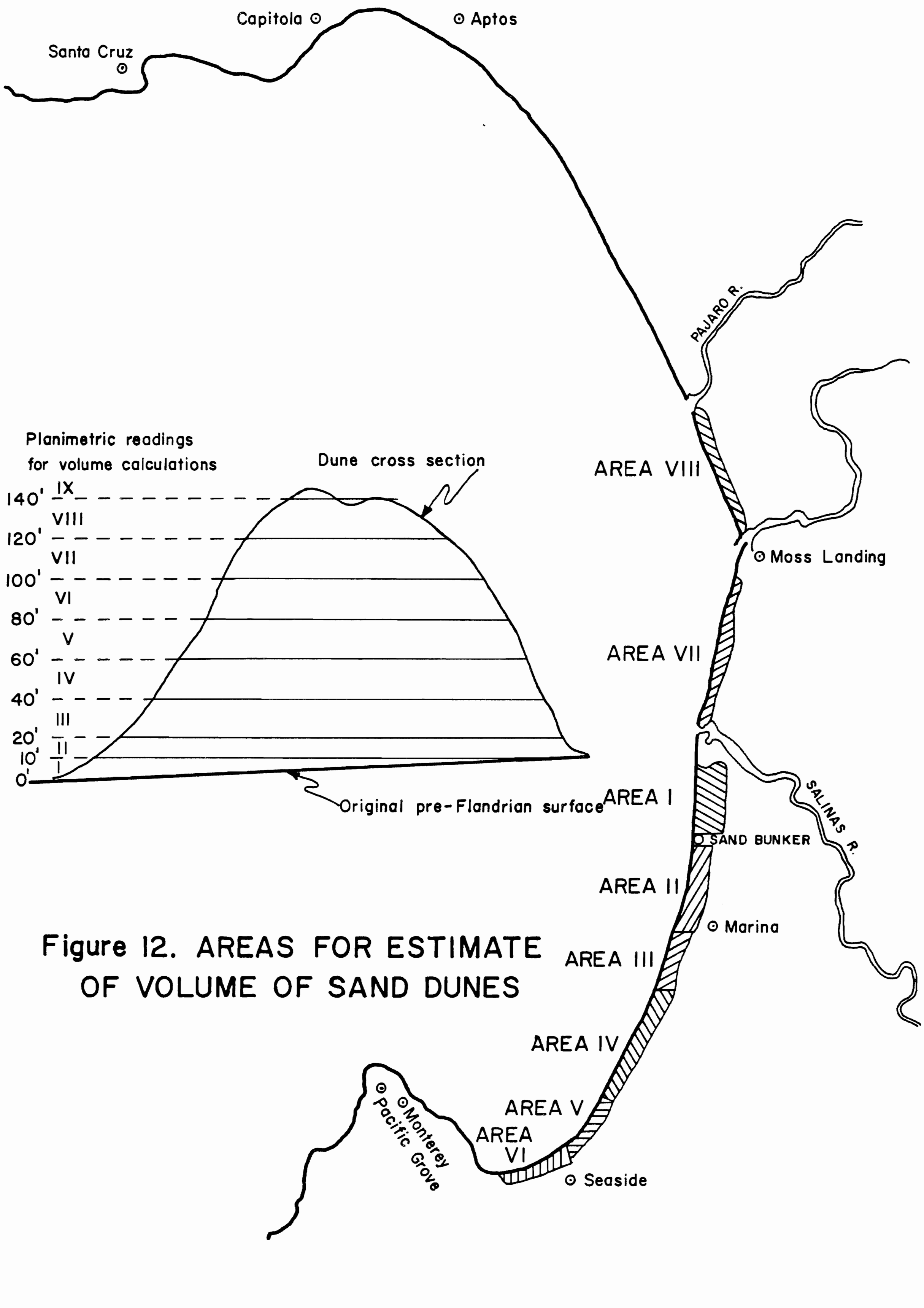



Figure 12. AREAS FOR ESTIMATE OF VOLUME OF SAND DUNES

The pre-Flandrian surface on which the Flandrian dunes have accumulated is approximately at sea-level along the shore (Cooper 1967) and has a gentle upward slope away from shore (Figure 12). By calculating the volume of successive "slices" of dunes as shown in Figure 12 and summing up for the eight areas shown, it is possible to obtain the total volume of sand blown away from the beaches during the past 3,000 to 5,000 years. The detail of the planimetric measurements and calculations is shown in the Appendix. Grand total volume of the dunes is 150,000,000 cubic yards of sand. Adding six per cent for the portion of beach sand finer than dune sand that must have been blown away, we estimate that 160 million cubic yards of sand have been removed from the beach since the beginning of Flandrian time 3,000 to 5,000 years ago.

Accordingly, the total amount of sand loss by deflation per year amounts to 53,000 to 32,000 cubic yards respectively. Under conditions prevailing today the deflation losses for Monterey Bay are approximately equal to the downcanyon transport, but would represent about one-tenth or less of the longshore transport.

Losses by Sand Mining Operations The simplest method to obtain a numerical value of the volume of sand extracted by mining would be to go to each mining operator and ask him to supply a number giving the total of their mining operations. Naively, we followed this route and found that each operator is very secretive about his production and sales. They have apparently instructed their employees as well not to reveal any information concerning the company business. This attitude has become even stricter in recent years as the pointed questions raised by aggressive conservationists regarding coastline recession due to mining make them more conscious of the long term effect of their operations.

Another method of evaluating the mining sand loss is to search the literature. Hart (1966) discusses the mineral resources of Monterey County based on information collected up to 1963. His section on "Sand and Gravel" (pages 84-107) gives data that permit a good estimate of the tonnage of sand extracted by each company operating a plant using beach sand as a source of material. In 1962 four companies were working five modern beach deposits and one older beach deposit. Dune sand in small amounts is mixed with the beach sand, which is coarser. Granite Construction Company (Figure 9) obtains beach sand from the surf zone by dragline scraper. The sand is moved to a surge pile and is later carried to a batch plant by conveyor. The capacity of the batch plant is about 100 tons per hour. In 1960 it operated an average of two days per week for a yearly production of 80,000 tons.

Monterey Sand Company (Figure 9) is the operator for two major sand deposits along Monterey Bay, one in Marina and one in Sand City. In both deposits beach sand is obtained by dragline scrapers from the surf zone. The beach plant at Sand City has a capacity of 80 tons per day and is operated an average of five days per week. The Marina plant capacity is at least equal. Total yearly production for Monterey Sand Company must exceed 50,000 tons.

Pacific Cement and Aggregates, Inc. operates two plants: the Lapis deposit two miles north of Marina, and the Prattco deposit about one mile north of Seaside. Most of the production of the Lapis plant, at least 90%, comes from older beach deposits located inland and therefore does not constitute a loss for sand budget calculation. Some beach sand washed over a sand bar at a beach site nearest the inland plant is extracted by means of a small, floating pipe dredge and sent to the main inland plant. Perhaps 10,000 tons per year is obtained in this fashion. The Prattco deposit plant has an estimated capacity of 50 tons per hour and is operated throughout the year for a production of 100,000 tons. Total production for this company must exceed 110,000 tons per year.

Seaside Sand and Gravel Company operates a plant in Marina immediately north of that of the Monterey Sand Company. Sand is obtained from the surf zone by dragline scrapers. Most of it is sold for sand blasting purposes. Production of the plant is similar to that of the Monterey Company plant and amounts to about 30,000 tons per year.

If the tonnage of sand extracted by the different companies is added, an annual grand total of approximately 270,000 tons is obtained for the period of the early sixties. If this is converted from tons (2,000 pounds) to cubic yards (2,900 pounds), we obtain a total of 190,000 cubic yards per year. With the great building upsurge of the early seventies, an important increase in sand mining has taken place. Today sand losses due to mining must amount to 250,000 to 300,000 cubic yards per year.

# V. SUMMARY

The sand budget for Monterey Bay shows that nearly $2.0 \times 10^6$ cubic yards of sand are delivered each year to Monterey Bay. Rivers contribute 60%, coastal erosion 25% and transport from the north about 15%.

Annual longshore transport in the north Bay increases from $2 \times 10^5$ cubic yards near Santa Cruz to $6 \times 10^5$ at the mouth of the Pajaro River which is close to a convergence of longshore transport. On the other hand, a divergence occurs near the head of Monterey Canyon at Moss Landing. Longshore downcoast transport, $9 \times 10^5$ cubic yards, is maximum near the mouth of the Salinas River. Further south, there appears to be a convergence with offshore transport near Marina.

Offshore deposition amounts to 6 to $7 \times 10^5$ cubic yards per year in the north Bay. This is accounted for readily by the amount of longshore transport coming in from the north by river supply and coastal erosion. In the south Bay annual offshore deposition amounts to $2.0 \times 10^6$ cubic yards; adding mining operations makes it a $2.2 \times 10^6$ cubic yards loss. Supply by river and coastal erosion is not enough to account for such a volume; hence the sand budget has a large delivery deficit in that area. This is perhaps made up by shoreward transport from deeper water by long period waves, a possibility suggested by Bowen and Inman (1966).

## VI. CONCLUSIONS AND RECOMMENDATIONS

In evaluating the results of the tentative sand budget for Monterey, we offer the following comments. The noteworthy and surprising result of our work is in regard to the present role of Monterey Canyon. Data from different sources point to a lack of importance today for the Monterey Submarine Canyon head as an avenue for transport of nearshore sediment to deeper water. This is supported by direct observations by divers, by examination of the longshore component of wave transport as determined from wave refraction diagrams, and by repeated bottom sampling in the axis of the upper reaches of the canyon that shows only fine sediments. We do not claim that the Monterey Submarine Canyon is a "dead canyon," but we are stating that the evidence indicates to us that little shallow water sediment moves into deeper water through the head of the submarine canyon. Examination of results of volumetric transport and deposition indicates that all the sediment delivered to Monterey Bay since the early 1900's and some deposited earlier can be accounted for without any transport downcanyon.

The historical records indicate that the Salinas River was emptying in the late 1800's into Monterey Bay at a point located about a mile north of Moss Landing, then called Morse's Landing, as shown on the 1859 edition of the USC&GS chart of Monterey Bay. About 1908, the Salinas River, either as a delayed effect of the 1906 earthquake or by man's action, started to debouch at its present location about four miles south of Moss Landing. Prior to that change in course, about 1908, the Salinas River was then delivering a large volume of sand at or near the head of Monterey Canyon. It is possible that a great deal of that sand moved downcanyon at that time which would account for the half million cubic yards per year estimated by Wilde (1968) as the contribution of Salinia to the Monterey Fan. However, it appears that this situation has changed completely since the Salinas River changed its course in 1908.

Another important conclusion of our study is the large amount of coastal erosion taking place south of the mouth of the Salinas River especially. This was discussed under "Supply by Coastal Erosion." Additional evidence is given by the two photographs in Figure 13. The lower photograph shows the sand bunker of one of the sand mining companies operating today. It is located two to 300 yards inland, the normal position for sand mining. The upper photograph shows an old sand bunker that was operating in the thirties and forties. It has now gone over the brink. Since originally it was located at least 200 yards inland, we must conclude that nearly 200 yards of shoreline recession has taken place there. This has been verified in conversation with personnel of sand mining companies.

We want to emphasize that coastal erosion undoubtedly would take place even if the sand mining companies were not operation. However, mining operations in the area where maximum erosion occurs do make the process worse in its effects.

Upon completion of this study to estimate the sand budget for Monterey Bay, several recommendations come to mind. Some are technical, some are political. Results of this study are interesting enough to

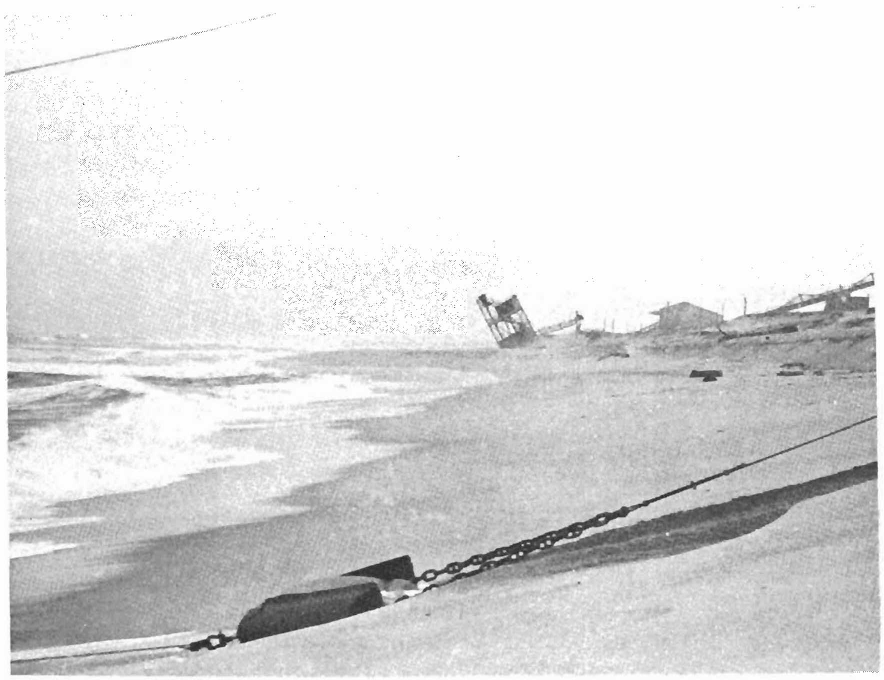
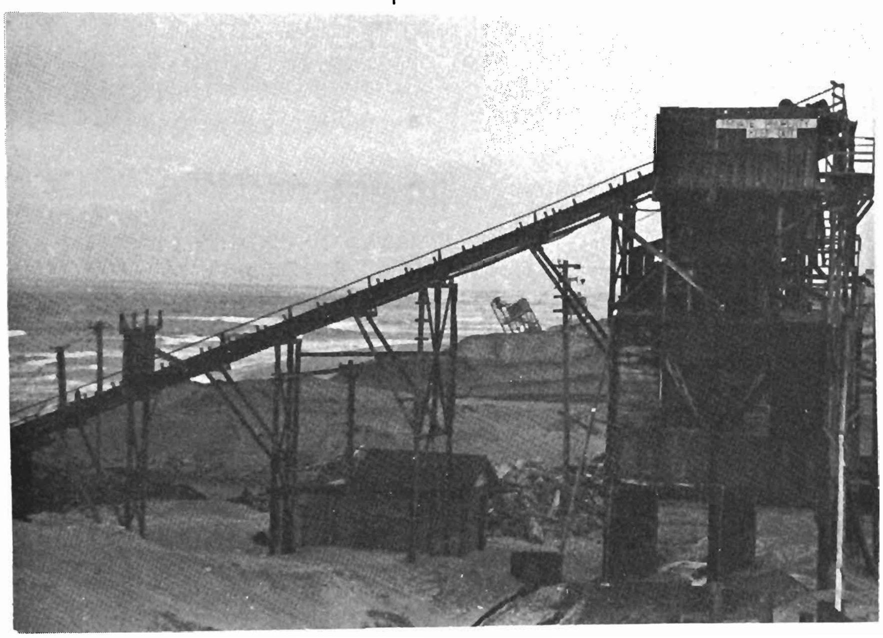


FIGURE 13 -- Evidence of Coastal Erosion.

Upper photograph shows an old sand bunker that has gone over the brink due to coastal erosion.

Lower photograph shows a modern and operating sand bunker located 200 to 300 yards inland for normal operation.



warrant continuing the investigation. This is especially true for the sand transport section and for the volumetric changes due to deposition. Regarding sand transport we recommend adding four stations for longshore calculations, as follows: one located two miles north of the Pajaro River, one located about a mile and a half north of Moss Landing Harbor, one located about a mile and a half south of Moss Landing Harbor, and one located about one mile south of the Salinas River mouth. Another recommendation would be to make the calculations on a monthly basis. This is especially important for the stations around the entrance to Moss Landing Harbor. This might show that for certain months the longshore components both north and south of Moss Landing are directed toward one another, in contrast to an average computed for the entire year.

Regarding calculations of volumetric changes due to deposition, we recommend evaluating the changes that have taken place between 1948 to 1950, the time of the last survey done for this study, and 1973 since a precise new survey has recently been completed for a research project of the U.S. Geological Survey Marine Geology Branch. This would allow us to verify, for another period, 1950 to 1973, that deposition of most sediment continues to take place near the mouth of the Salinas and Pajaro Rivers as it did between 1908 and 1950.

Political recommendations will be short and based strictly on scientific evidence as we do not wish to deal with environmental emotionalism. In view of the high rate of erosion south of the mouth of the Salinas River, we recommend:

1) Finding alternate sources of sand supply for the sand mining companies. Even though they are not solely responsible for coastal erosion, their activity makes a bad situation worse. It is therefore desirable that sand mining along the coast be terminated, especially north of Fort Ord.
2) Extreme caution on the part of public officials concerned in granting building permits in coastal dune areas as they are likely to be geologically ephemeral. Since the municipalities incur a certain degree of responsibility in approving a building project, they may find themselves in the position of having to spend a great number of tax dollars to protect a project that, with a little foresight, would not have been approved.

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# VIII. APPENDIX

## DETAIL OF CALCULATIONS FOR ESTIMATE OF VOLUME OF FLANDRIAN DUNES

NOTE 1: The method of calculation and location of sections are discussed in the section entitled "Losses by Deflation." Anything less than 0.1 square inch within a topographic contour was not measured with a planimeter but read on transparent graph paper to the twentieth of an inch. This permits, with a magnifying glass, an easy estimate of $\frac{1}{400}$ of a square inch and is thus more accurate than a planimeter reading for a small area.

NOTE 2: Reading I is area from 0 feet elevation at the shore to 10' at the back of the dunes where the position of the ten foot contour is taken as that of the 20 foot contour.

Section I

| | | |
|---|---|---|
| Reading I | | 18,400,000 square feet |
| Reading II | | 17,080,000 square feet |
| Average | = | 17,740,000 square feet |
| Times half of 10' | = | 88,700,000 cubic feet |
| Volume | = | 3,285,000 cubic yards |
| | | |
| Reading II | | 17,080,000 square feet |
| Reading III | | 12,040,000 square feet |
| Average | = | 14,560,000 square feet |
| Times 10' | = | 145,600,000 cubic feet |
| Volume | = | 5,393,000 cubic yards |

| | | |
|---|---|---|
| Reading III | | 12,040,000 square feet |
| Reading IV | | 6,120,000 square feet |
| Average | = | 9,080,000 square feet |
| Times 20' | = | 181,600,000 cubic feet |
| Volume | = | 6,726,000 cubic yards |
| Reading IV | | 6,120,000 square feet |
| Reading V | | 1,800,000 square feet |
| Average | = | 3,960,000 square feet |
| Times 20' | = | 79,200,000 cubic feet |
| Volume | = | 2,933,000 cubic yards |
| Reading V | | 1,800,000 square feet |
| Reading VI (Graph paper) | | 290,000 square feet |
| Average | = | 1,045,000 square feet |
| Times 20' | = | 20,900,000 cubic feet |
| Volume | = | 774,000 cubic yards |
| Reading VI (Graph paper) | | 290,000 square feet |
| Reading VII (Graph paper) | | 50,000 square feet |
| Average | = | 170,000 square feet |
| Times 20' | = | 3,400,000 cubic feet |
| Volume | = | 126,000 cubic yards |
| Total Sand Volume Section I | = | 19,237,000 cubic yards |

Section II

Reading I - 0' shore to 10' back (taken as 20' contour).

| | | |
|---|---|---|
| Reading I | | 18,560,000 square feet |

Reading II - 10' estimated (run between shore and 20' contour) to 10' back (taken as 20' contour).

| | | |
|---|---|---|
| Reading II | | 17,520,000 square feet |
| Average | = | 18,040,000 square feet |
| Times half of 10' | = | 90,200,000 cubic feet |
| Volume | = | 3,341,000 cubic yards |
| | | |
| Reading II | | 17,520,000 square feet |
| Reading III - 20' contour | | 15,920,000 square feet |
| Average | = | 16,720,000 square feet |
| Times 10' | = | 167,200,000 cubic feet |
| Volume | = | 6,193,000 cubic yards |
| | | |
| Reading III | | 15,920,000 square feet |
| Reading IV | | 11,480,000 square feet |
| Average | = | 13,700,000 square feet |
| Times 20' | = | 274,000,000 cubic feet |
| Volume | = | 10,148,000 cubic yards |
| | | |
| Reading IV | | 11,480,000 square feet |
| Reading V | | 6,400,000 square feet |
| Average | = | 8,940,000 square feet |
| Times 20' | = | 178,800,000 cubic feet |
| Volume | = | 6,622,000 cubic yards |

| | | | |
|---|---|---|---|
| Reading V | | | 6,400,000 square feet |
| Reading VI | | | 3,360,000 square feet |
| | Average | = | 4,880,000 square feet |
| | Times 20' | = | 97,600,000 cubic feet |
| Volume | | = | 3,615,000 cubic yards |
| Reading VI | | | 3,360,000 square feet |
| Reading VII | | | 1,400,000 square feet |
| | Average | = | 2,380,000 square feet |
| | Times 20' | = | 47,600,000 cubic feet |
| Volume | | = | 1,763,000 cubic yards |
| Reading VII | | | 1,400,000 square feet |
| Reading VIII (graph paper) | | | 470,000 square feet |
| | Average | = | 935,000 square feet |
| | Times 20' | = | 18,700,000 cubic feet |
| Volume | | = | 693,000 cubic yards |
| Reading VIII (graph paper) | | | 470,000 square feet |
| Reading IX (graph paper) | | | 48,000 square feet |
| | Average | = | 259,000 square feet |
| | Times 20' | = | 5,180,000 cubic feet |
| Volume | | = | 192,000 cubic yards |
| Total Sand Volume Section II | | = | 32,566,000 cubic yards |

Section III

Reading I - 0' shore to 10' back (taken as 20' contour)

| | | |
|---|---|---|
| Reading I | | 8,760,000 square feet |
| Reading II (10' estimated run between shore and 20' contour) | | |
| Reading II | | 8,240,000 square feet |
| Average | = | 8,500,000 square feet |
| Times half of 10' | = | 42,500,000 cubic feet |
| Volume | = | 1,574,000 cubic yards |
| | | |
| Reading II | | 8,240,000 square feet |
| Reading III | | 7,000,000 square feet |
| Average | = | 7,620,000 square feet |
| Times 10' | = | 76,200,000 cubic feet |
| Volume | = | 2,822,000 cubic yards |
| | | |
| Reading III | | 7,000,000 square feet |
| Reading IV | | 6,800,000 square feet |
| Average | = | 6,900,000 square feet |
| Times 20' | = | 138,000,000 cubic feet |
| Volume | = | 5,111,000 cubic yards |
| | | |
| Reading IV | | 6,800,000 square feet |
| Reading V | | 4,840,000 square feet |
| Average | = | 5,820,000 square feet |
| Times 20' | = | 116,400,000 cubic feet |
| Volume | = | 4,311,000 cubic yards |

| | | |
|---|---|---|
| Reading V | | 4,840,000 square feet |
| Reading VI | | 3,160,000 square feet |
| Average | = | 4,000,000 square feet |
| Times 20' | = | 80,000,000 cubic feet |
| Volume | = | 2,963,000 cubic yards |
| Reading VI | | 3,160,000 square feet |
| Reading VII | | 1,560,000 square feet |
| Average | = | 2,360,000 square feet |
| Times 20' | = | 47,200,000 cubic feet |
| Volume | = | 1,748,000 cubic yards |
| Reading VII | | 1,560,000 square feet |
| Reading VIII | | 520,000 square feet |
| Average | = | 1,040,000 square feet |
| Times 20' | = | 20,800,000 cubic feet |
| Volume | = | 770,000 cubic yards |
| Reading VIII | | 520,000 square feet |
| Reading IX | | 0 square feet |
| Average | = | 260,000 square feet |
| Times 20' | = | 5,200,000 cubic feet |
| Volume | = | 193,000 cubic yards |
| Total Volume Section III | = | 19,493,000 cubic yards |

Section IV

Reading I - 0' shore to 10' (taken as 20' contour)

| | | |
|---|---|---|
| Reading I | | 16,360,000 square feet |
| Reading II (10' estimated run between shore and 20' contour) | | |
| Reading II | | 15,280,000 square feet |
| Average | = | 15,820,000 square feet |
| Times half of 10' | = | 79,100,000 cubic feet |
| Volume | = | 2,930,000 cubic yards |
| Reading II | | 15,280,000 square feet |
| Reading III | | 14,520,000 square feet |
| Average | = | 14,900,000 square feet |
| Times 10' | = | 149,000,000 cubic feet |
| Volume | = | 5,519,000 cubic yards |
| Reading III | | 14,520,000 square feet |
| Reading IV | | 13,680,000 square feet |
| Average | = | 14,100,000 square feet |
| Times 20' | = | 282,000,000 cubic feet |
| Volume | = | 10,444,000 cubic yards |
| Reading IV | | 13,680,000 square feet |
| Reading V | | 11,040,000 square feet |
| Average | = | 12,360,000 square feet |
| Times 20' | = | 247,200,000 cubic feet |
| Volume | = | 9,155,000 cubic yards |

| | | |
|---|---|---|
| Reading V | | 11,040,000 square feet |
| Reading VI | | 6,400,000 square feet |
| Average | = | 8,720,000 square feet |
| Times 20' | = | 174,400,000 cubic feet |
| Volume | = | 6,459,000 cubic yards |
| Reading VI | | 6,400,000 square feet |
| Reading VII | | 3,400,000 square feet |
| Average | = | 4,900,000 square feet |
| Times 20' | = | 98,000,000 cubic feet |
| Volume | = | 3,630,000 cubic yards |
| Reading VII | | 3,400,000 square feet |
| Reading VIII | | 1,480,000 square feet |
| Average | = | 2,440,000 square feet |
| Times 20' | = | 48,800,000 cubic feet |
| Volume | = | 1,807,000 cubic yards |
| Reading VIII | | 1,480,000 square feet |
| Reading IX | | 560,000 square feet |
| Average | = | 1,020,000 square feet |
| Times 20' | = | 20,400,000 cubic feet |
| Volume | = | 756,000 cubic yards |
| Total Volume Section IV | = | 40,700,000 cubic yards |

Section V

Reading I - o' to 10' in back taken as 20' contour

| | | |
|---|---|---|
| Reading I | | 11,066,666 square feet |
| Reading II - Estimated between shore and 20' contour | | |
| Reading II | | 10,320,000 square feet |
| Average | = | 10,693,300 square feet |
| Times half of 10' | = | 53,467,000 cubic feet |
| Volume | = | 1,980,000 cubic yards |
| | | |
| Reading II | | 10,320,000 square feet |
| Reading III | | 8,760,000 square feet |
| Average | = | 9,540,000 square feet |
| Times 10' | = | 95,400,000 cubic feet |
| Volume | = | 3,533,000 cubic yards |
| | | |
| Reading III | | 8,760,000 square feet |
| Reading IV | | 6,640,000 square feet |
| Average | = | 7,700,000 square feet |
| Times 20' | = | 154,000,000 cubic feet |
| Volume | = | 5,704,000 cubic yards |
| | | |
| Reading IV | | 6,640,000 square feet |
| Reading V | | 3,440,000 square feet |
| Average | = | 5,040,000 square feet |
| Times 20' | = | 100,800,000 cubic feet |
| Volume | = | 3,733,000 cubic yards |

| | | |
|---|---|---|
| Reading V | | 3,440,000 square feet |
| Reading VI | | 1,480,000 square feet |
| Average | = | 2,460,000 square feet |
| Times 20' | = | 49,200,000 cubic feet |
| Volume | = | 1,822,000 cubic yards |
| Reading VI | | 1,480,000 square feet |
| Reading VII | | 640,000 square feet |
| Average | = | 1,060,000 square feet |
| Times 20' | = | 21,200,000 cubic feet |
| Volume | = | 785,000 cubic yards |
| Reading VII | | 640,000 square feet |
| Reading VIII | | 240,000 square feet |
| Average | = | 440,000 square feet |
| Times 20' | = | 8,800,000 cubic feet |
| Volume | = | 326,000 cubic yards |
| Reading VIII | | 240,000 square feet |
| Reading IX | | 80,000 square feet |
| Average | = | 160,000 square feet |
| Times 20' | = | 3,200,000 cubic feet |
| Volume | = | 119,600 cubic yards |
| Total Volume Section V | = | 18,002,000 cubic yards |

Section VI

| | | | |
|---|---|---|---|
| Reading I | | 8,160,000 | square feet |
| Reading II | | 7,520,000 | square feet |
| Average | = | 7,840,000 | square feet |
| Times half of 10' | = | 39,200,000 | cubic feet |
| Volume | = | 1,452,000 | cubic yards |
| Reading II | | 7,520,000 | square feet |
| Reading III | | 5,080,000 | square feet |
| Average | = | 6,300,000 | square feet |
| Times 10' | = | 63,000,000 | cubic feet |
| Volume | = | 2,333,000 | cubic yards |
| Reading III | | 5,080,000 | square feet |
| Reading IV | | 2,960,000 | square feet |
| Average | = | 4,020,000 | square feet |
| Times 20' | = | 80,400,000 | cubic feet |
| Volume | = | 2,978,000 | cubic yards |
| Reading IV | | 2,960,000 | square feet |
| Reading V | | 800,000 | square feet |
| Average | = | 1,880,000 | square feet |
| Times 20' | = | 37,600,000 | cubic feet |
| Volume | = | 1,393,000 | cubic yards |
| Total Volume Section VI | = | 8,156,000 | cubic yards |

Section VII

| | | |
|---|---|---|
| Reading I | | 17,400,000 square feet |
| Reading II | | 12,320,000 square feet |
| Average | = | 14,860,000 square feet |
| Times half of 10' | = | 74,300,000 cubic feet |
| Volume | = | 2,752,000 cubic yards |
| | | |
| Reading II | | 12,320,000 square feet |
| Reading III | | 5,240,000 square feet |
| Average | = | 8,780,000 square feet |
| Times 10' | = | 87,800,000 cubic feet |
| Volume | = | 3,252,000 cubic yards |
| | | |
| Reading III | | 5,240,000 square feet |
| Reading IV | | 1,880,000 square feet |
| Average | = | 3,560,000 square feet |
| Times 10' | = | 35,600,000 cubic feet |
| Volume | = | 1,319,000 cubic yards |
| | | |
| Reading IV | | 1,880,000 square feet |
| Reading V | | 440,000 square feet |
| Average | = | 1,160,000 square feet |
| Times 10' | = | 11,600,000 cubic feet |
| Volume | = | 430,000 cubic yards |

| | | |
|---|---|---|
| Reading V | | 440,000 square feet |
| Reading VI | | 120,000 square feet |
| Average | = | 280,000 square feet |
| Times 10' | = | 2,800,000 cubic feet |
| Volume | = | 104,000 cubic yards |
| Total Volume Section VII | = | 7,856,000 cubic yards |

Section VIII

| | | |
|---|---|---|
| Reading I | | 9,440,000 square feet |
| Reading II | | 7,640,000 square feet |
| Average | = | 8,540,000 square feet |
| Times half of 10' | = | 42,700,000 cubic feet |
| Volume | = | 1,581,000 cubic yards |
| Reading II | | 7,640,000 square feet |
| Reading III | | 2,760,000 square feet |
| Average | = | 5,200,000 square feet |
| Times 10' | = | 52,000,000 cubic feet |
| Volume | = | 1,926,000 cubic yards |
| Reading III | | 2,760,000 square feet |
| Reading IV | | 360,000 square feet |
| Average | = | 1,560,000 square feet |
| Times 10' | = | 15,600,000 cubic feet |
| Volume | = | 578,000 cubic yards |
| Total Volume Section VIII | = | 4,085,000 cubic yards |

Grand total volume for all Flandrian dunes

| | | |
|---|---|---|
| Sections I to VIII | = | 150,093,000 cubic yards |

| | |
|---|---|
| In 2,500 years | 60,000 cubic yards per year |
| In 3,100 years | 48,000 cubic yards per year |
| In 5,000 years | 30,000 cubic yards per year |

APPENDIX TABLE I

SALINAS RIVER ANNUAL WATER DISCHARGE IN ACRE-FEET
FOR THE PERIOD 1931 TO 1971

| Water Year | Discharge | Water Year | Discharge |
|---|---|---|---|
| 1931 | 1,920 | 1952 | 668,300 |
| 1932 | 641,000 | 1953 | 114,600 |
| 1933 | 19,400 | 1954 | 71,180 |
| 1934 | 88,400 | 1955 | 1,950 |
| 1935 | 224,700 | 1956 | 393,900 |
| 1936 | 384,400 | 1957 | 1,700 |
| 1937 | 641,300 | 1958 | 668,500 |
| 1938 | 1,398,000 | 1959 | 123,200 |
| 1939 | 14,860 | 1960 | 24,950 |
| 1940 | 540,300 | 1961 | 991 |
| 1941 | 1,776,000 | 1962 | 121,400 |
| 1942 | 533,900 | 1963 | 176,200 |
| 1943 | 744,700 | 1964 | 26,820 |
| 1944 | 290,100 | 1965 | 55,800 |
| 1945 | 293,000 | 1966 | 28,970 |
| 1946 | 132,300 | 1967 | 554,100 |
| 1947 | 6,980 | 1968 | 11,310 |
| 1948 | 3,260 | 1969 | 1,477,000 |
| 1949 | 50,580 | 1970 | 162,700 |
| 1950 | 29,440 | 1971 | 36,950 |
| 1951 | 35,430 | | |

26 year average 1931 to 1956 equals 349,611 acre-feet per year.

15 year average 1957 to 1971 equals 231,372 acre-feet per year.