Effects of the Santa Cruz Harbor on Coastal Processes of Northern Monterey Bay, California

G. B. Griggs and
R. E. Johnson

Division of Applied Sciences, University of California
Santa Cruz, California 95064, U.S.A.

ABSTRACT / An average of 230,000 cubic meters of sand is provided to the beaches of northern Monterey Bay each year by littoral transport from upcoast and from local river input. Two jetties constructed as part of a small craft harbor interrupted the littoral flow of sand and significantly altered the area's natural coastal processes. A wide protective beach immediately formed upcoast against a formerly retreating beach cliff. Sand now filling the harbor mouth each winter has led to expensive yearly dredging as well as seasonally or permanently depleted downcoast beaches. Seacliff retreat, always a problem in the area, is caused primarily by surf attack of weaker stratigraphic units and erosion along joint sets and faults, causing collapse of the bluffs. The seasonal loss of protective beaches has led to a two- to three-fold increase in the rate of downcoast cliff retreat following harbor construction except where protective rip-rap has been emplaced by property owners.

Received Oct. 31, 1975

Introduction

The construction of small craft harbors and marinas along the Pacific coast has repeatedly led to sedimentation and erosion problems, due in part to an incomplete understanding or a disregard for littoral processes. Two jetties constructed as part of a harbor project at Santa Cruz, California, interrupted the littoral drift of sand. A wide beach was formed on the upcoast side and the beaches downcoast were quickly deprived of sand. Residents downcoast claimed harbor construction increased cliff erosion rates, endangering homes and lowering property values. Rip-rap has been emplaced by many landowners at considerable expense. Further to the south, the city of Capitola claimed the jetties had starved their beach, driving away summer tourists. A beach was subsequently built at considerable cost. Within the Santa Cruz Harbor itself, the sand deposited in the channel each winter has left the harbor either unusable or extremely hazardous for three to four months each year. As a result, yearly dredging of the harbor mouth has been necessary.

Did the jetties deprive the downcoast beaches of sand and as a consequence accelerate erosion of the seacliffs? An investigation was conducted (1) to determine the effects of harbor construction on the littoral drift and beaches, and (2) to compare rates of seacliff and beach erosion before and after harbor construction. The results should be valuable in assessing the feasibility and environmental impact of future coastal projects in similar settings.

Geologic and Oceanographic Setting

Santa Cruz lies on the northern edge of Monterey Bay, some 110 km south of San Francisco on the California coast. The Santa Cruz mountains flanking the study area consist of a crystalline plutonic and metamorphic core overlain or lapped by Tertiary sediments. These mountains are drained by a number of small coastal streams including the San Lorenzo River which is the largest drainage entering northern Monterey Bay. The mountains are heavily vegetated. Average annual rainfall varies from 50 cm near the coast to 150 cm on the upper western slopes. The climate is characterized by dry summers and wet winters with more than 90 percent of the precipitation occurring between November and May.

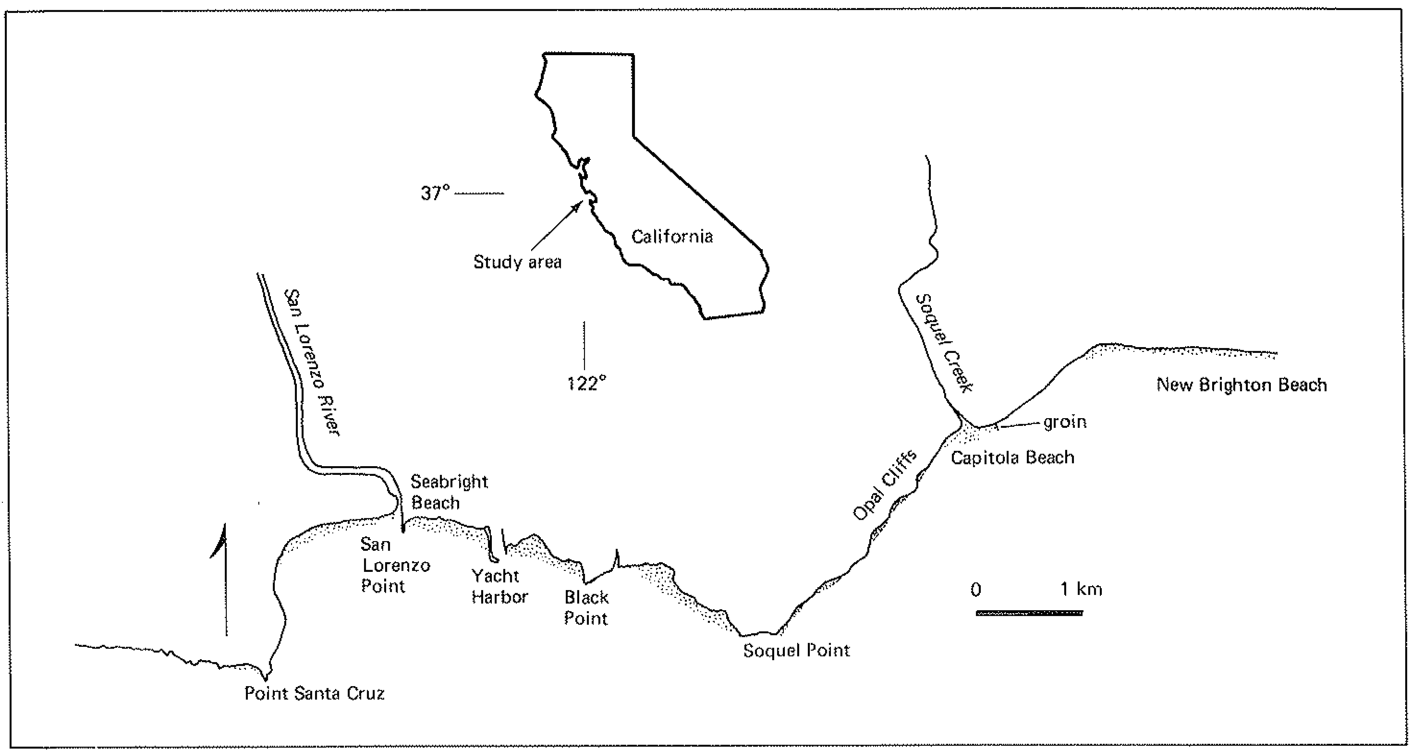
Uplifted marine terraces flank most of northern Monterey Bay and also the open coast to the north. The lowest terrace forms the top of the present seacliff which varies in height from about 6 to 27 m. North of the bay the coast consists of steep cliffs broken every 2 or 3 km by sandy pocket beaches which have formed at the mouths of the coastal streams. Immediately upon entering the northern portion of the bay, sandy beaches become more prominent and extensive (Fig. 1).

The oceanographic conditions which prevail in Monterey Bay have been discussed by Wolf (1970) and Yancey (1968). Yearly average swell is from the west-northwest, and because the northern margin of the bay is where the shoreline is at variance with these prevailing wave fronts, refraction results in a strong component of eastward littoral drift in the area. This eastward drift is believed to move beach sand into the inner portion of the bay from beaches along the headlands and open coast to the northwest.

Harbor Planning and Construction

For some years local interest in Santa Cruz desired a protected small-boat harbor to serve the existing fishing fleet and prospective recreational craft on a year-round basis. The U.S. Army Corps of Engineers (1958) suggested that Woods Lagoon, a drowned river mouth about a kilometer east of the mouth of the San Lorenzo River, be improved northward to form the harbor, and that parallel rubble-mound jetties be provided to protect the entrance channel. The plan proposed by the U.S. Army Corps of Engineers included the improvement (dredging) of Woods Lagoon with an entrance channel, an inner harbor, and a turning basin. Dredge spoil was deemed suitable for deposition be-

Figure 1. Study area in northern Monterey Bay, California showing pertinent coastal features.



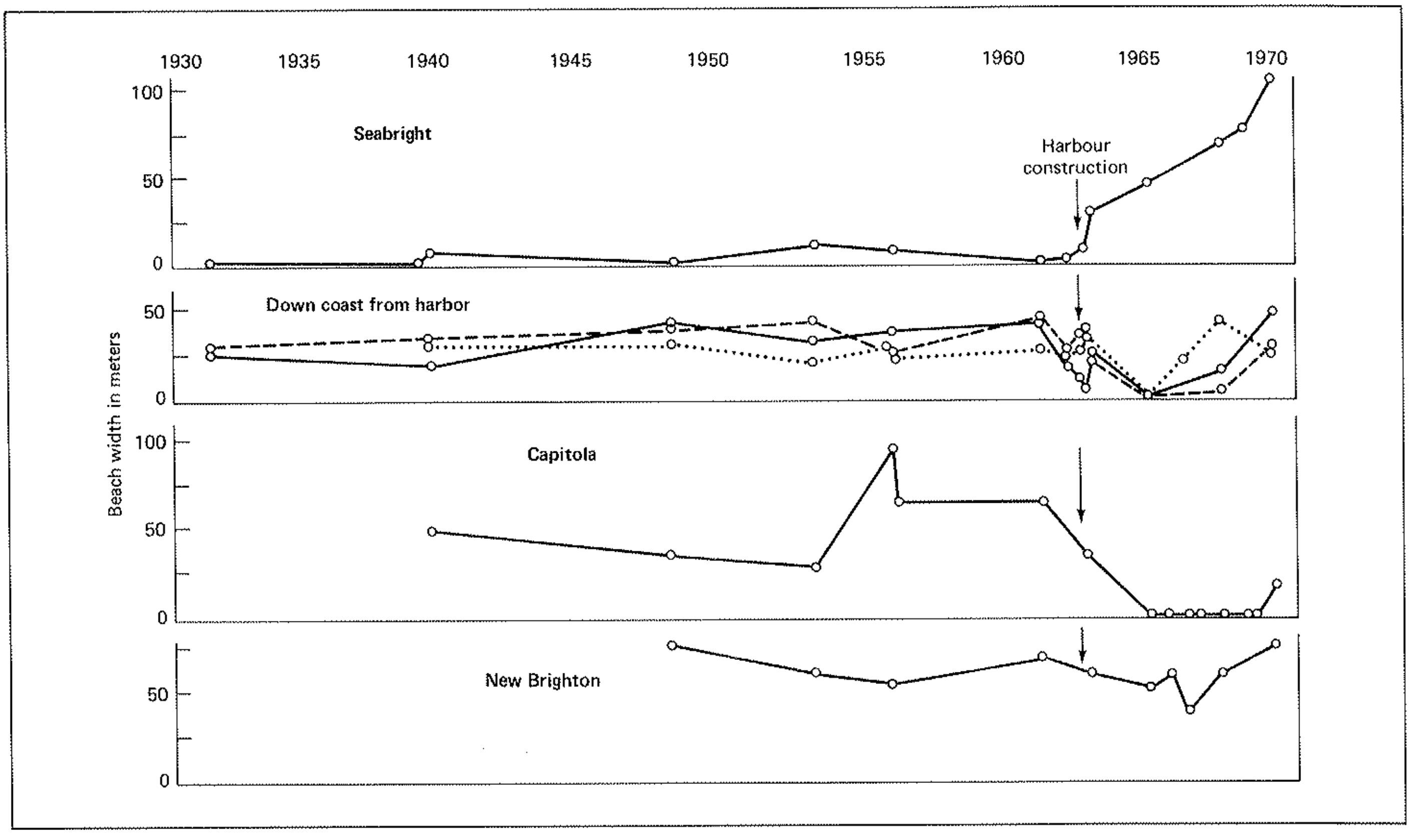


Figure 2. Chronologic changes in the widths of beaches upcoast and downcoast from the Santa Cruz harbor before and after harbor construction.

hind bulkheads, raising the edges of the lagoon. It would also provide nourishment for the adjacent beaches. The following conclusions are drawn from the harbor feasibility study concerning the environmental conditions of the area:

(1) The predominant littoral transport is downcoast. Reversals occur at the proposed harbor area, and in other areas of Monterey Bay.

(2) Erosion in the northern part of the bay will continue because the alignment of the coast is conducive to rapid movement of littoral drift out of the area.

(3) Estimates by the Corps of Engineers on the average net rate of downcoast littoral drift from an experimental groin study and other work in the bay, ranged from 20,000 m^3 to a possible maximum of 230,000 m^3 annually.

(4) Jetties would form littoral barriers which would benefit the upcoast beaches but would probably cause erosion of the coast to the south and east. If the net annual downcoast rate of littoral drift approached 230,000 m^3 erosion would be rapid and continuous. Pocket beaches would be denuded and bluff erosion accelerated immediately downcoast.

(5) The possible harmful effects of jetty construction could be offset initially by depositing sandy material, obtained as a byproduct from the harbor dredging, on the downcoast beaches and offset permanently by providing a means of annually bypassing 230,000 m^3 of littoral material.

(6) Should the annual rate of littoral drift approach the lower estimate of 20,000 m^3 the damaging effects of the jetties would be much less pronounced. A sand-bypassing system would not be required and maintenance dredging of the harbor could provide the downcoast beach material. Construction of the sand bypassing plant should, therefore, be deferred until its needs were demonstrated.

Construction at the Woods Lagoon site began in late 1962. By December the west jetty was nearing completion and sand was accreting on the updrift (west side). By August 1963 the cliffs along the area immediately upcoast were flanked by a sandy beach varying in width from 15 to 17 m. Beach surveys between November 1962 and November 1964 indicated a 460,000 m^3 accumulation of sand, or an average rate of littoral drift of 230,000 m^3/year. Subsequent data and discussion will indicate that these 2 years were not extreme and were probably near average in terms of sand production and transport. The harbor was first dredged in 1965, and yearly dredging has been required ever since.

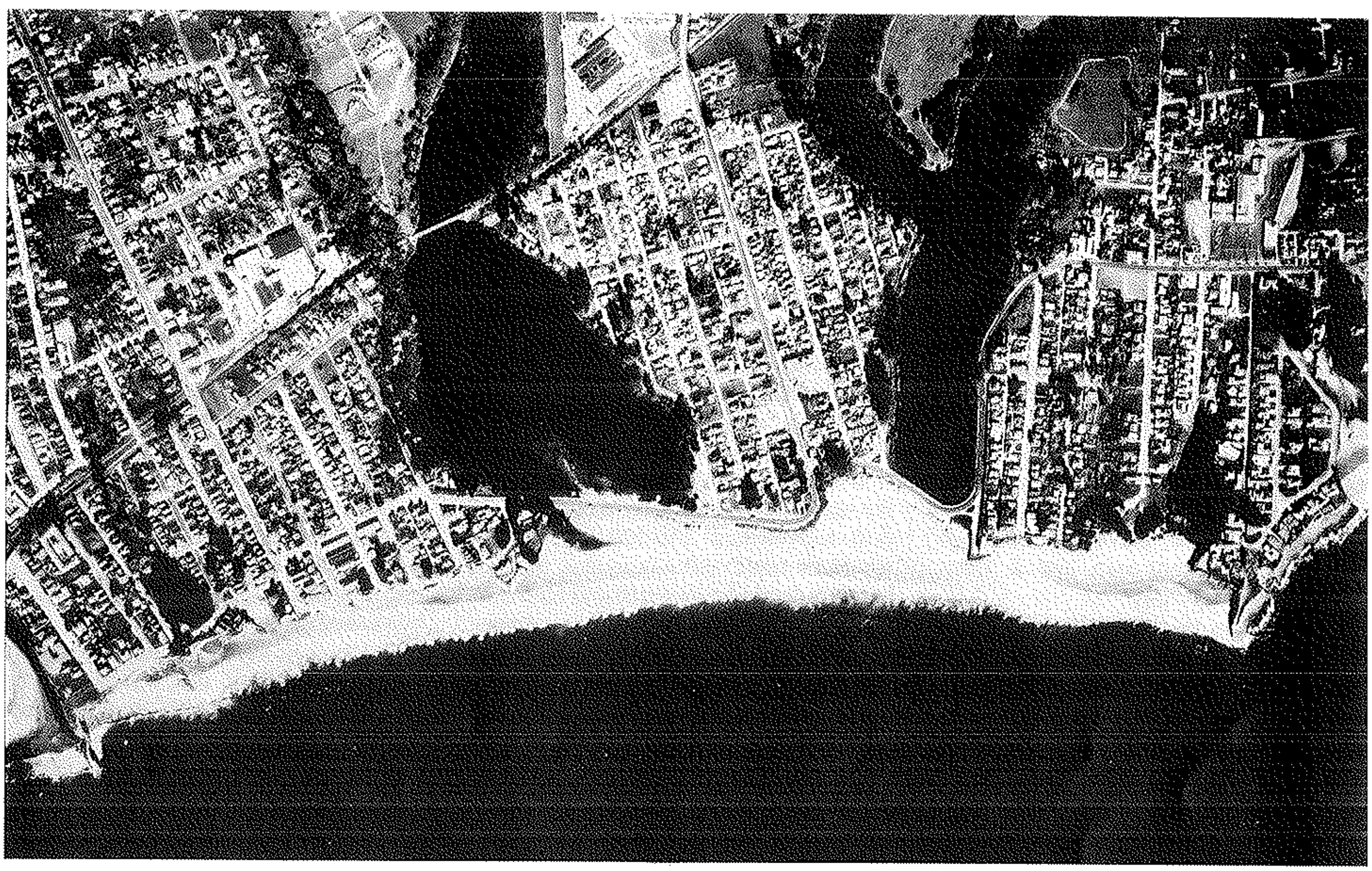
Sources of sand

The two-year sand accumulation, a composite of the sediment from the San Lorenzo River and littoral drift from the northwest, came from upcoast. Each sediment source is important because the significance of the jetties as littoral obstructions is a function of where sediments enter the system.

San Lorenzo River. The contribution of the San Lorenzo River to the littoral budget can be partly evaluated on the basis of comparative heavy mineralogy and also on some preliminary sediment discharge measurements. Average percentages of four dominant heavy minerals in sands from the river and beaches, immediately upcoast and downcoast, were compiled (Table 1) from the data of Yancey (1968), Yancey and Wilde (1971), and Sayles (1966). The heavy minerals in the beach sands indicate a very small contribution from the San Lorenzo River. The abundances of each mineral from the upcoast beaches is remarkably similar to those downcoast. River mineralogy is distinct from both, but its effect on downcoast mineralogy seems insignificant. Hypersthene, garnet, and green hornblende all show changes in the opposite sense from that expected from a river dilution. The time of the year when samples were collected, or the river discharges prior to sampling, could affect the apparent influence of the river, but over time these differences should average out and the river's influence on the beach, if large, should be obvious.

The bed of the San Lorenzo River does contain a significant amount of sand which is in transit to the beaches. Results of several years of bed and suspended load sampling in the river indi-

Figure 3. Coastline between San Lorenzo Point and Black Point prior to harbor construction. Photograph taken December 1961.



cate in an average year the river may contribute 50 to 70,000 m^3 (22-30 percent of the annual littoral drift) of beach material. One very large storm and flood, however, could significantly alter these figures.

On the basis of available information, the San Lorenzo River is an important source but it does not appear to be the dominant contributor to the beach sand budget in northern Monterey Bay.

Upcoast littoral drift. The volume of littoral drift entering northern Monterey Bay is a composite of sediment contributed both by seacliff erosion and by streams from Santa Cruz and San Mateo counties. The coastal streams contribute small amounts of sediment, and because seacliff erosion in the mudstone cliffs of northern Santa Cruz county is slow, little additional sediment is provided there. However, the San Mateo coastline further north consists mostly of sandstone and granite, both good providers of sand. Yancey (1968) shows an augite rich province in beach sands extending from San Mateo county down the coast to the

Table 1 Comparative Heavy Mineralogy of Beach and River Sand

In percent of total heavy minerals.

	Green hornblende	Augite	Hypersthene	Garnet
Upcoast Beaches (average of 9)	33.8	36.1	14.0	1.9
San Lorenzo River (average of 4)	51.3	16	6.5	9.4
Downcoast Beaches (average of 11)	33.5	33.5	20.4	1.5

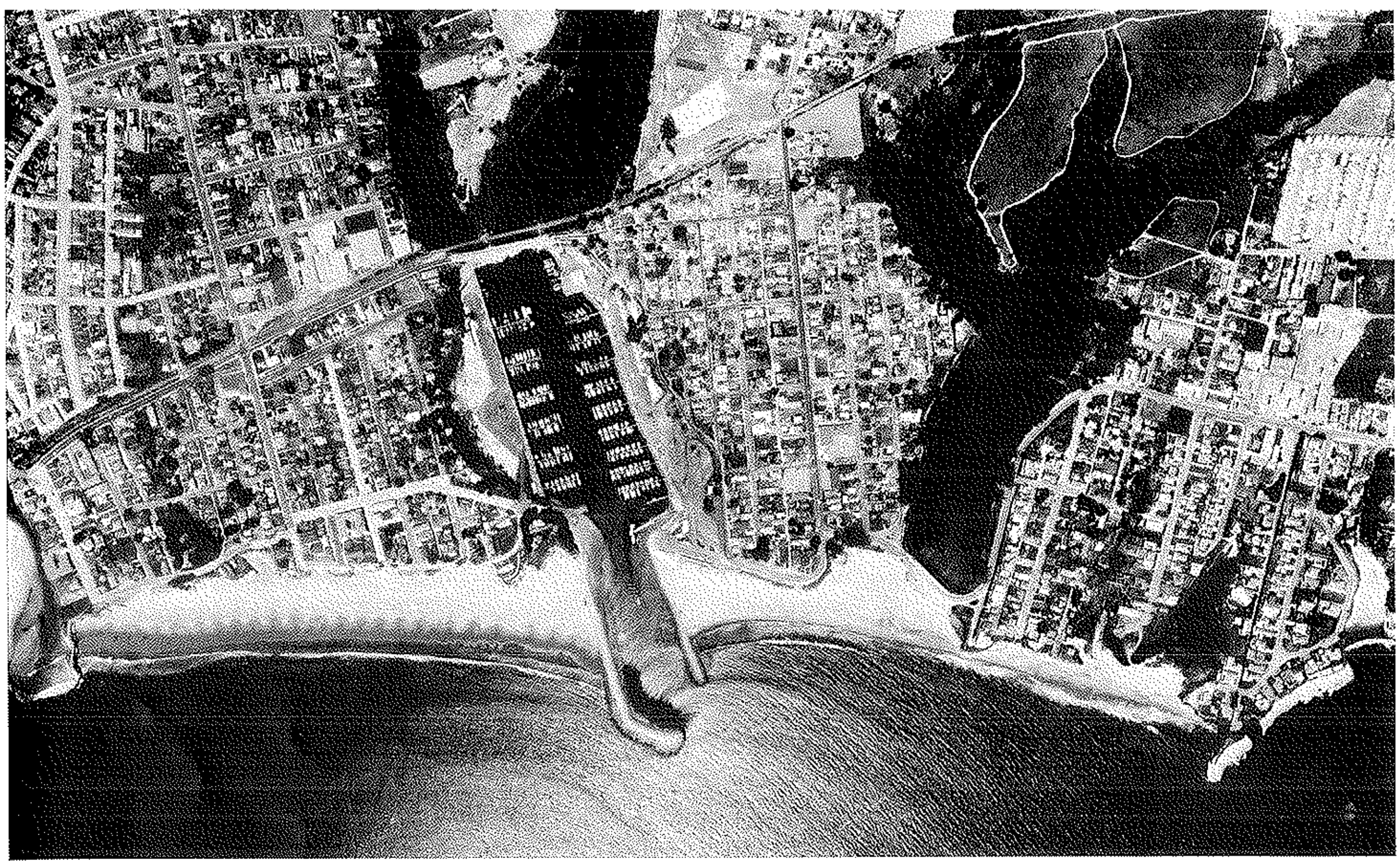


Figure 4. Coastline between San Lorenzo Point and Black Point following harbor construction. Photograph taken May 1965.

Figure 5. Capitola Beach prior to harbor construction; note width of beach. Photograph taken December 1961.

northern end of Monterey Bay. A large influx of sand into what is normally a rocky bottom at Point Santa Cruz is often noted shortly after the onset of a winter storm and/or a period of strong swell from the northwest. From estimates of the area affected, the thickness of the sand, and the annual number of large storms (derived from interviews with local residents, aerial photographs, and change in wave refraction patterns) approximate upcoast littoral transport volumes of 160,000 to 185,000 m^3/year have been computed. On the basis of the somewhat limited existing information on sand supply, it appears that the major contributor to the northern Monterey Bay beaches is littoral drift from the north.

Coastal Changes Following Harbor Construction

Changes in beach size and sand distribution

The buildup of 460,000 m^3 of sand upcoast from the west jetty following harbor construction was the first indication that the yacht harbor was affecting "normal" coastal processes. Aerial photographs taken between 1931 and 1970 were analyzed along with other documents in order to determine the overall changes in both the beaches and in rates of cliff erosion. Measurements of beach widths were made at six sites, one upcoast from the harbor and five downcoast (Fig. 2). Measurements were made on photographs taken at the same time of the year to reduce normal seasonal variations in beach width.

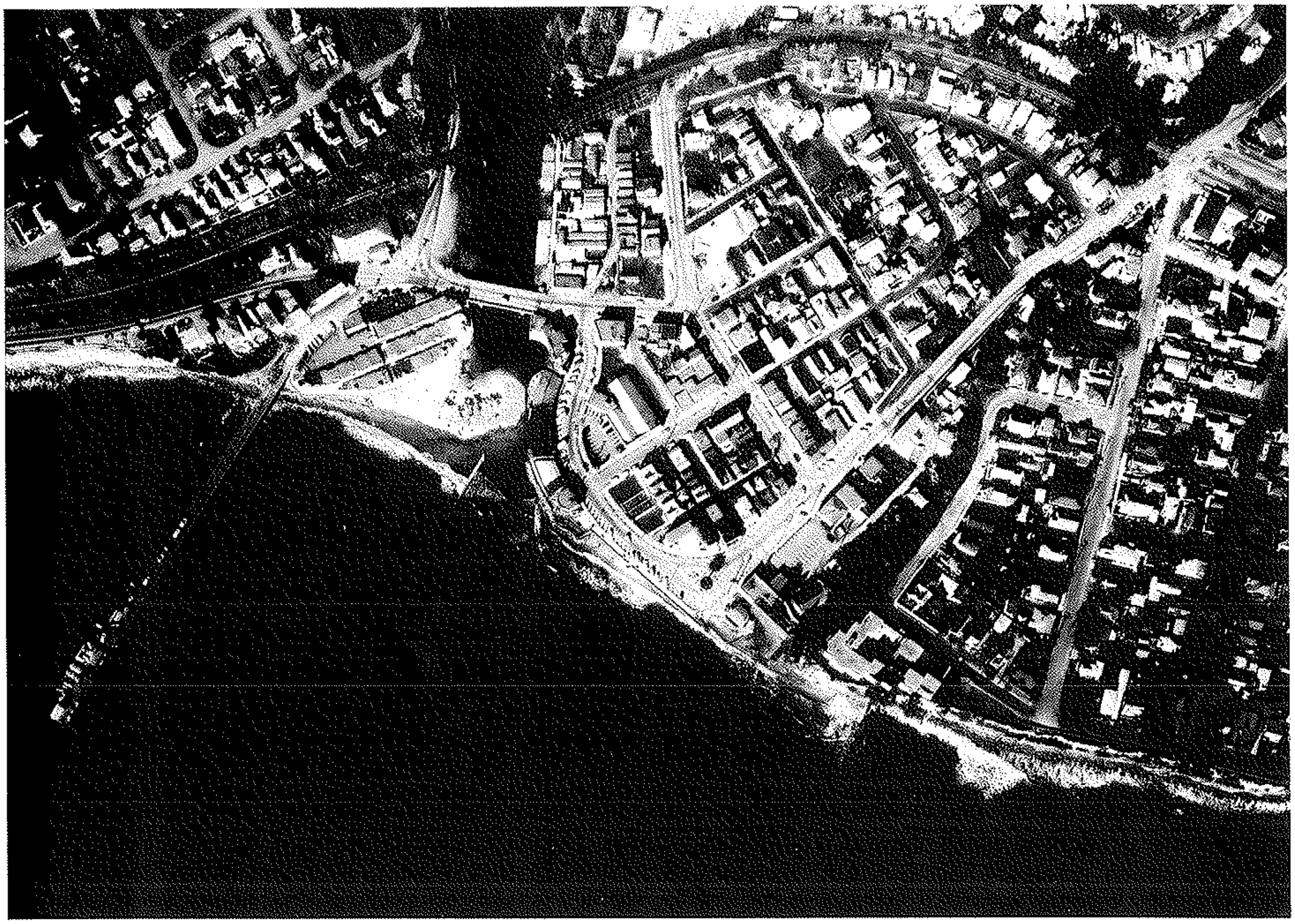


Figure 6. Capitola Beach following harbor construction; note lack of beach. Photograph taken November 1965.

Upcoast from harbor. The stretch of coast from the mouth of the San Lorenzo River to the west jetty is backed almost entirely by steep bluffs about 14 m high. During most of the year prior to harbor construction, practically no beach was exposed at high tide and the bluffs were subjected to wave attack during high tide or storm periods. Serious recession of the bluffs was occurring, at least four sections of a city road at the edge of the cliff had fallen into the sea, and a number of houses were also threatened (Fig. 3). With jetty construction, a beach rapidly began to form along these cliffs. During subsequent summer months a sandy beach, at times over 120 m wide, has formed here (Fig. 4). The width of Seabright Beach has increased more than twelve times (Fig. 2), and cliffs here are now well protected from wave attack.

The harbor area. Following the initial buildup of 460,000 m^3 of sand against the west jetty, sand continued to build up, moving out along the jetty and around its tip into the harbor where it became a hazard to navigation. Approximately 54,000 m^3 of material was initially dredged out and pumped onto the beach immediately downcoast. Each winter the harbor mouth has been virtually closed by the sand buildup. Dredging has been required each spring; as of May 1974, approximately 570,000 m^3 of material had been removed from the harbor at a cost of about $1,750,000 (Table 2). The average volume of materiall dredged yearly since the upcoast beach reached equilibrium has been about 75,000 m^3.

Several lines of evidence indicate that the first two years of sand buildup

Table 2 Maintenance Dredging, Santa Cruz Harbor, 1965–1974

	Volume removed (m^3)
1965	53,500
1966	26,000
1967	43,500
1968	46,000
1969	60,000
1970	81,500
1971	83,000
1972	69,000
1973	84,000
1974	46,000

against the west jetty were average years and not extreme. The volume of sand contributed to the littoral budget in any one year is primarily a function of the frequency and intensity of storms. The increased wave action and precipitation will increase cliff erosion, sediment transport and discharge by streams, in addition to providing more energy for littoral drift. River discharge figures for the San Lorenzo River should be representative of the storms and sediment generation for the area. During the first two years of sand accumulation, no severe storms occurred, and of the total discharge figures for these two years, one is somewhat higher and one is much lower than the average yearly discharge. It seems reasonable to conclude from these data that littoral drift buildups during these two winters was not due to extreme flood conditions and should not be considered to be above average.

Anderson's calculations (1971) on potential littoral drift indicate wind waves and swell provide the energy to drift 230,000 to 270,000 m^3 of sand each year along the northern Monterey Bay coastline. The littoral drift rate determined from accretion of sand against the west jetty is consistent with the calculated available wave energy.

If 230,000 m^3 of sand per year moves along the coastline, but only 75,000 m^3 of material is dredged from the harbor each year, then some 155,000 m^3 of sand must be moving across the harbor mouth and is either being deposited somewhere or continuing on downcoast. Sand has continued to build up west of the jetty and has widened this beach. Aerial photographs and ground observations show shallow sand bars along the insides of both jetties and completely across the harbor mouth during winter and spring low tides. This is additional evidence of significant sand transport bypassing the jetties.

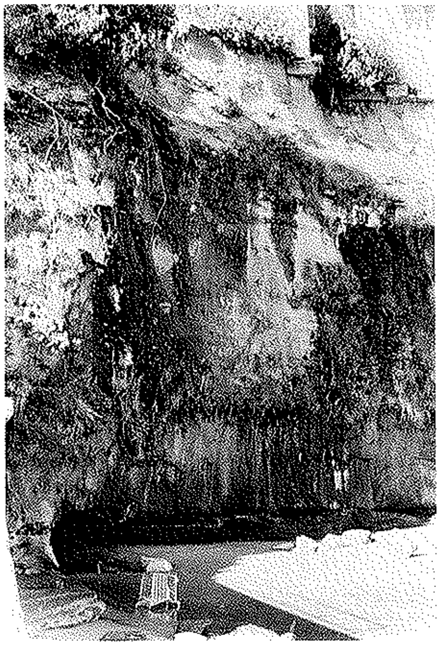
Downcoast: harbor to Capitola. The first 2 km downcoast from the harbor consists of low cliffs interrupted by beaches at the mouths of lagoons; these cliffs have been exposed directly to wave attack during much of the year both before and after harbor construction. The next 2 km from Soquel Point to Capitola consists almost entirely of cliffs with a similar history.

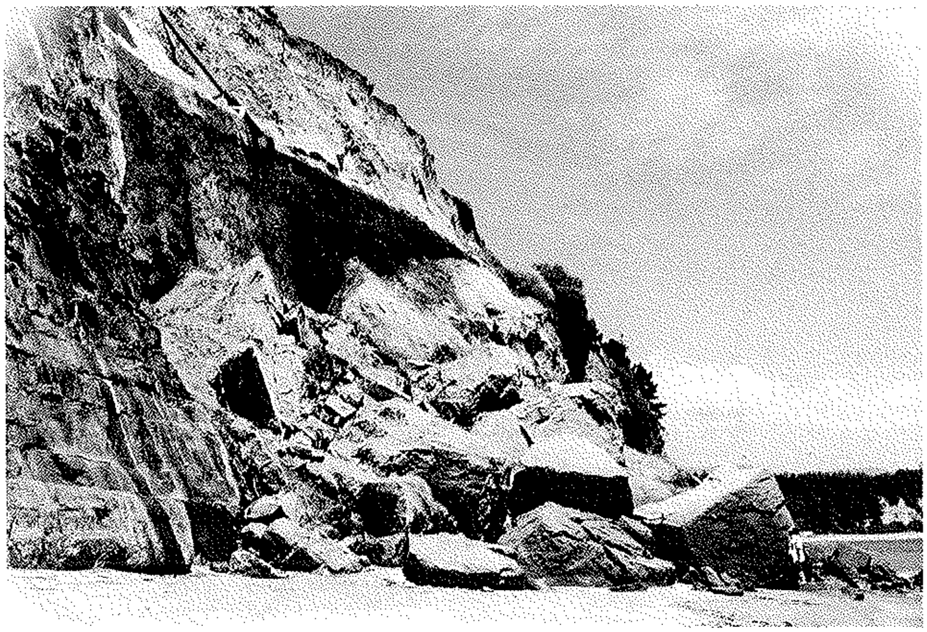
The widths of three beaches in this area showed a major decline in the first three years following harbor construction (Fig. 2). In more recent years the beach widths appear to be increasing to their original pre-harbor condition. However, the few data points are taken from aerial photographs. They can be greatly affected by the month of observation and the stage of the tide. In any case, the time elapsed before this apparent return to "normal" beach widths has been between six and eight years, or between six and eight winters of decreased protection against wave attack.

Capitola beach. The changes during recent years at Capitola, about 5 km downcoast from the harbor, are well documented. Aerial photographs of Capitola taken at various seasons of the year from 1932 to 1961 invariably show a wide or at least a moderately wide sandy beach (Fig. 5). Since harbor completion the beach has either been non-existent or of very limited extent throughout the year (Fig. 6). The average beach width has been reduced almost 90 percent, from about 56 m to 6 m (Fig. 2). As a result the waves began to attack the parking lot and street adjacent to the preexisting beach. To alleviate this situation and to provide a beach for the summer tourists on which the community depends, Capitola eventually contracted a firm (April 1970) to build a 75 m groin at the downcoast end of the beach and to bring in about 2,000 truckloads of local quarry sand. The cost of rebuilding the beach was $160,000, somewhat less than an earlier $420,000 plan proposed by the Corps of Engineers which involved two longer groins. At present a beach of at least moderate width exists throughout the year, and a wide sandy beach prevails during the summer months.

Four studies which deal with the Capitola beach problem deserve discussion. Based on a photograph of a wide muddy beach at Capitola following the extreme floods of December 1955, a report by Feibusch (1966) to the City of Capitola concluded that "the supply of sand by Soquel Creek is probably the major source of beach supply at Capitola". Because of "a deficiency in rainfall and runoff during the past 10 years, the sand supplied to Capitola beach has been inadequate and thus the beach has become seriously depleted". These conclusions are not substantiated, however, by either the photographic record, the runoff figures, or a second more detailed study (Anderson 1971). Moore (1972) agreed with Feibusch that Soquel Creek was the major contributor of beach sediment to Capitola beach, and that the harbor construction was therefore not a major factor in the loss of the beach. Moore explained the beach disappearance as due to a "mysterious" storm in the late summer of 1965 that denuded Capitola beach. After the storm, the natural constructive wave action did not replenish the beach "for some unknown reason".

Anderson (1971) computed potential littoral drift along this section of coast. He also estimated the amount of sand supplied to the beaches by cliff erosion between the harbor and Capitola, and from a Corps of Engineers report (1969)

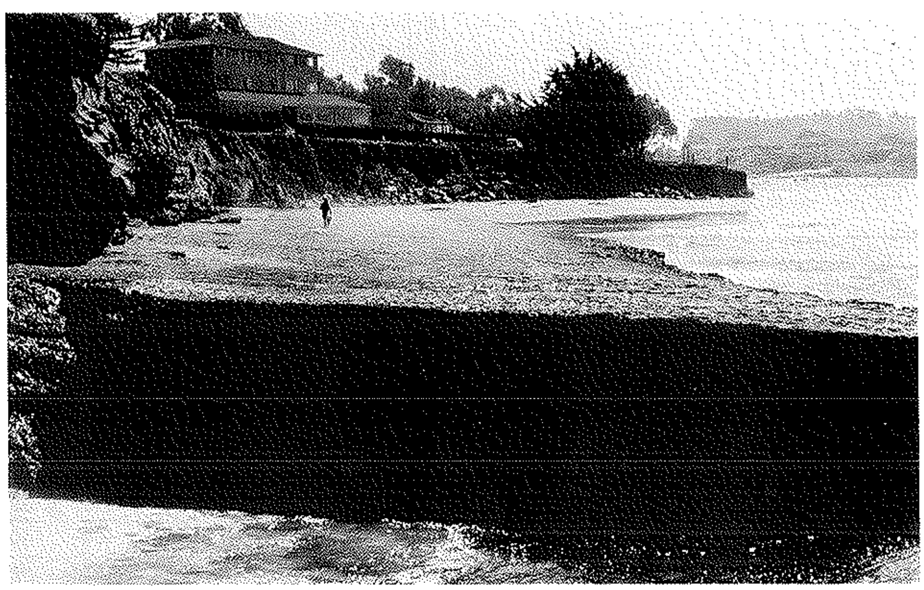




on Soquel Creek, reported an estimated annual input of 6,100 m^3 of sand to the beach from that source. This represents about 3 percent of the total sand supply available to the beach. The remainder comes from upcoast littoral drift (230,000 m^3 annually) and cliff erosion (2,900 m^3 annually). Anderson believed that the construction of the harbor at Santa Cruz was a major factor in the observed reduction in the size of the beach at Capitola which became evident in 1965. While approximately 460,000 m^3 of sand were building up against the west jetty, some 300,000 m^3 of "sandy material" dredged from the harbor were deposited on the beach immediately downcoast during this two-year period. This left a net annual deficit of 80,000 m^3 in the sand supply to Capitola beach, a 30 percent reduction. However, much of the "sandy material" was probably organic rich mud which is more characteristic of the low energy lagoonal environments along this stretch of coast, and therefore did not contribute to the beach sand budget. The 30 percent deficit is probably closer to 50 percent for the first two years. Inasmuch as the down-

Figure 7.(a) Seacliff consisting of Purisima Formation showing undercutting along non-resistant bed. Note the exposed foundations of the apartments at the top of the cliff. Photograph taken at low tide between Capitola and New Brighton Beach. (b) Photograph taken just to the right of 7(a). Joint sets parallel and normal to cliff face and undercutting have led to failure of large blocks. Note person in foreground for scale.

Figure 8. Bedrock terrace or shore platform which has been stripped of its terrace deposits. Photograph taken between Black Point and Soquel Point.



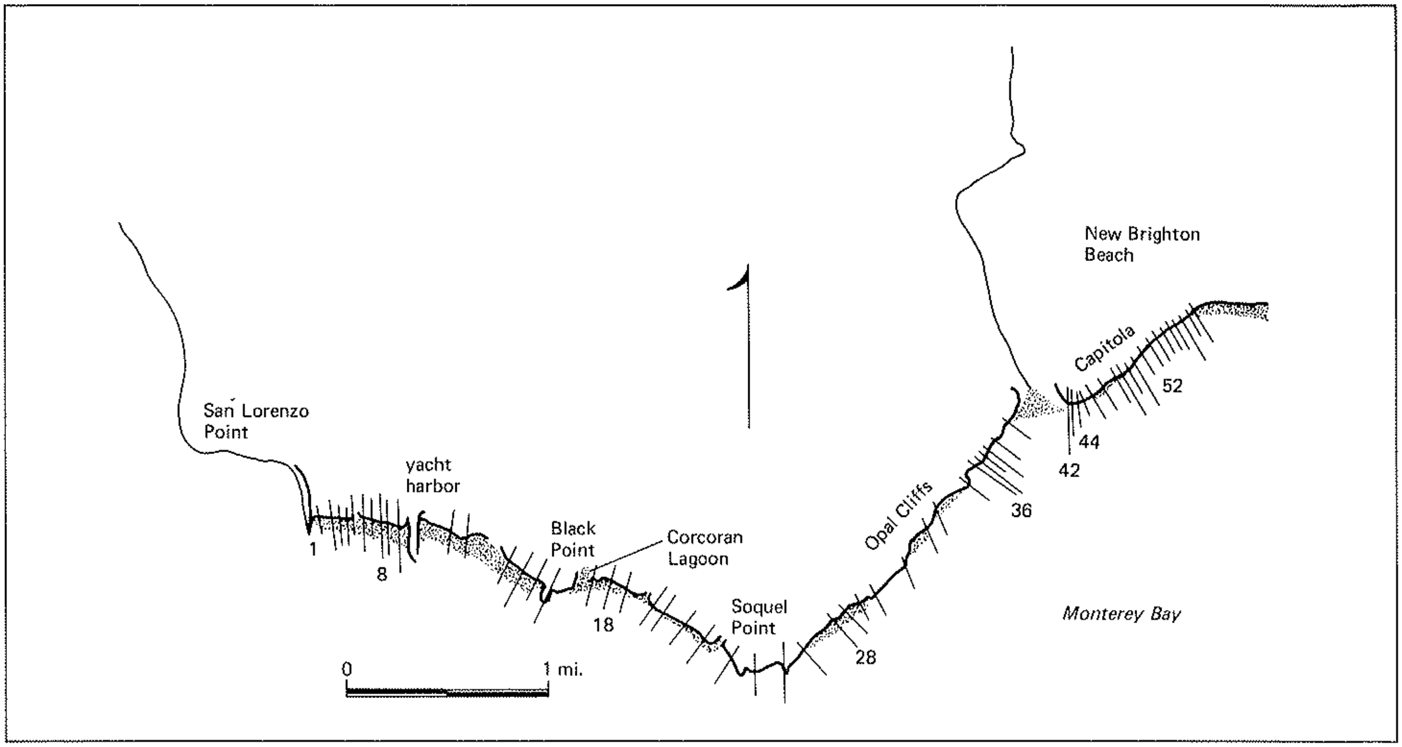
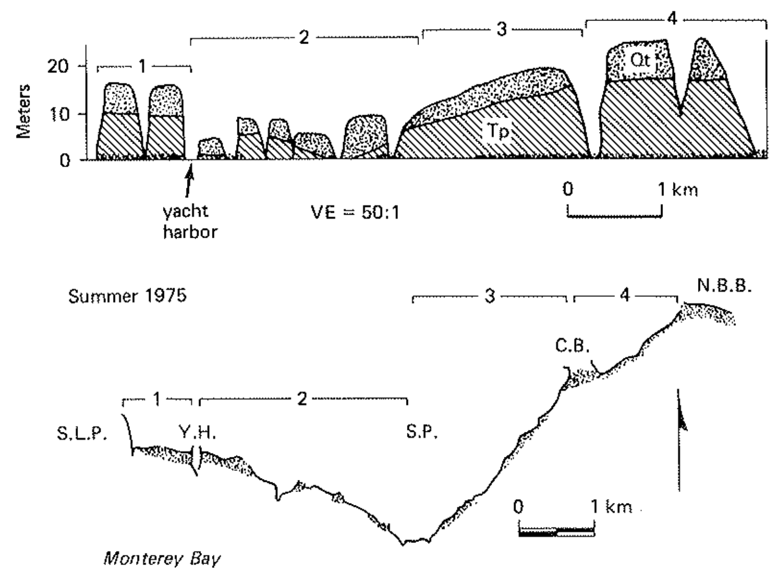


Figure 9. Locations of sites for seacliff erosion measurements.



			Subareas			
			1	2	3	4
Average rates of erosion (cm/yr)	Pre	1963	24	27	27	27
	Post	1963	6	15	27	33
Range of erosion rates	Pre	1963	48-12	40-6	48-9	40-18
	Post	1963	12-0	58-0	70-0	72-0

Figure 10. (a) This page: Average rates of erosion and range of erosion rates in four subareas between San Lorenzo Point and New Brighton Beach. Profile at top indicates stratigraphy of seacliff showing determination and relative position of Purisima Formation (Tp) and overlying terrace deposits (Qt). (b) Opposite page: Comparison of average rates of cliff erosion before and after harbor construction at individual sites between San Lorenzo Point and New Brighton Beach. Locations of landmarks and profiles are shown in Fig. 9.

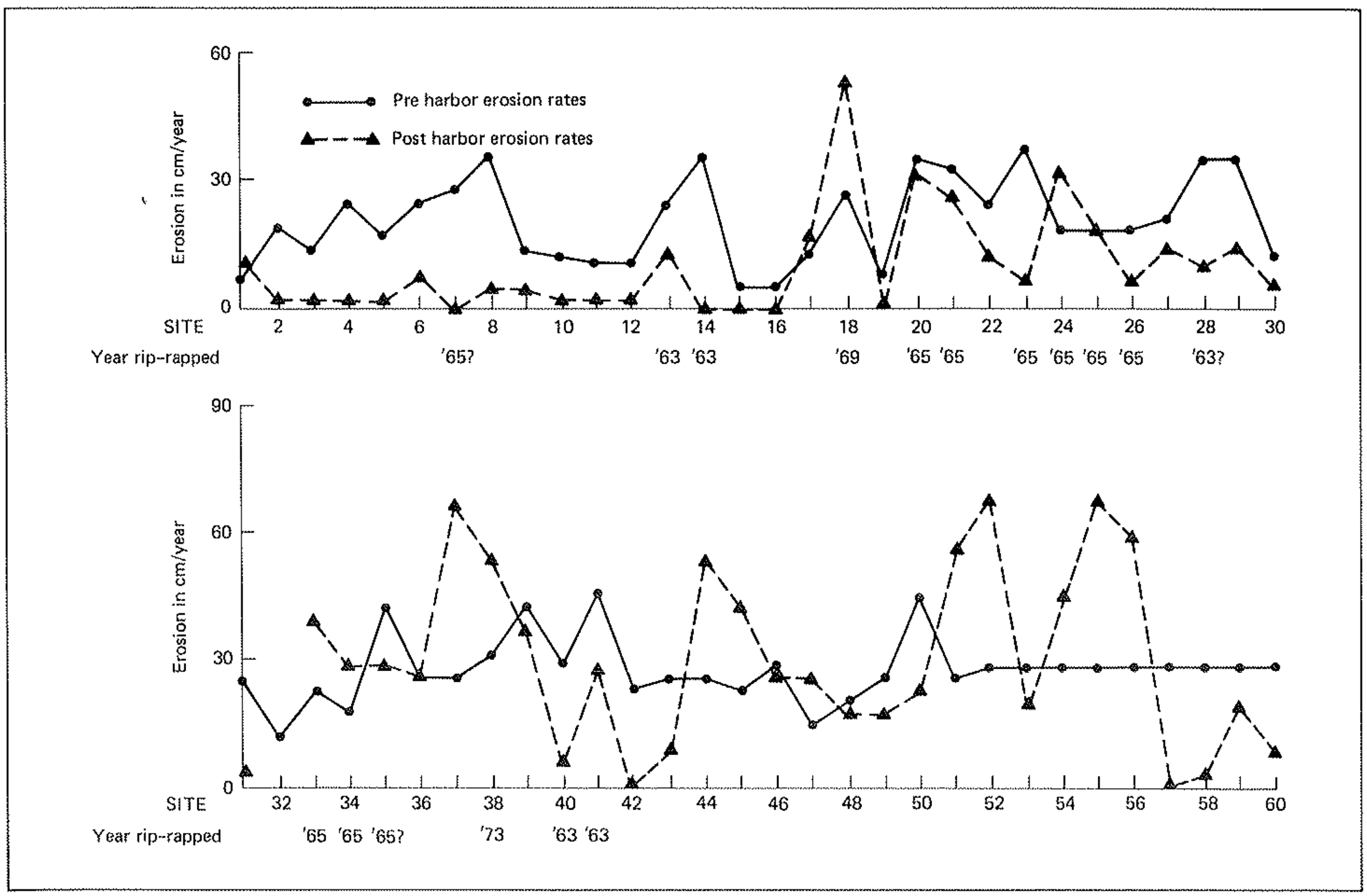
coast littoral drift potential at Capitola remained unaffected, an erosional condition of significant proportions existed at the beach for this period, resulting in a depleted beach (Anderson 1971).

Following harbor construction Anderson concluded that sand from the annual dredging has been returned to the littoral drift and thus conditions downcoast returned to normal. Even after harbor construction was completed and the annual dredging began, however, the beach remained depleted (Fig. 2). This was the reason for the artificial construction of a beach at Capitola. Although the annual sand budget downcoast may have been the same, the sand flow was not distributed uniformly throughout the year. Thirty percent of the sand is trapped in the harbor during the winter months and then dredged out and added to the beach during a short period in the spring. Thus during the period of winter wave attack, the Capitola beach was being starved each year by the sand accumulation in the harbor.

Downcoast from Capitola. East of Capitola the coast is backed by cliffs and was flanked by a narrow sandy beach at times prior to harbor construction for which photographs are available (June 1956 and December 1961). Since 1965 photographs reveal no beach and surf attacking the base of the cliff. Further eastward at New Brighton the trend of the coast undergoes an abrupt change from NE-SW to NW-SE and wide sandy beaches begin which continue into the bay. Waves incident on this portion of the bay, regardless of their original angle, would appear to approach the beach almost normal (Wiegel 1964) resulting in a much smaller component of littoral drift than the sections of the bay upcoast. The coast appears to have reached an equilibrium configuration. Average beach width at New Brighton has changed only slightly since harbor construction (Fig. 2). A slight decline followed by a more recent increase to pre-harbor width can be seen from the data.

Cliff Recession

The cliff recession study extends 7 km from the mouth of the San Lorenzo River eastward to New Brighton Beach (Fig. 1). Cliffs range in height from 6 to 27 m and consist of two geologic units: (1) interbedded marine sandstones and siltstones of the Pliocene Purisima For-



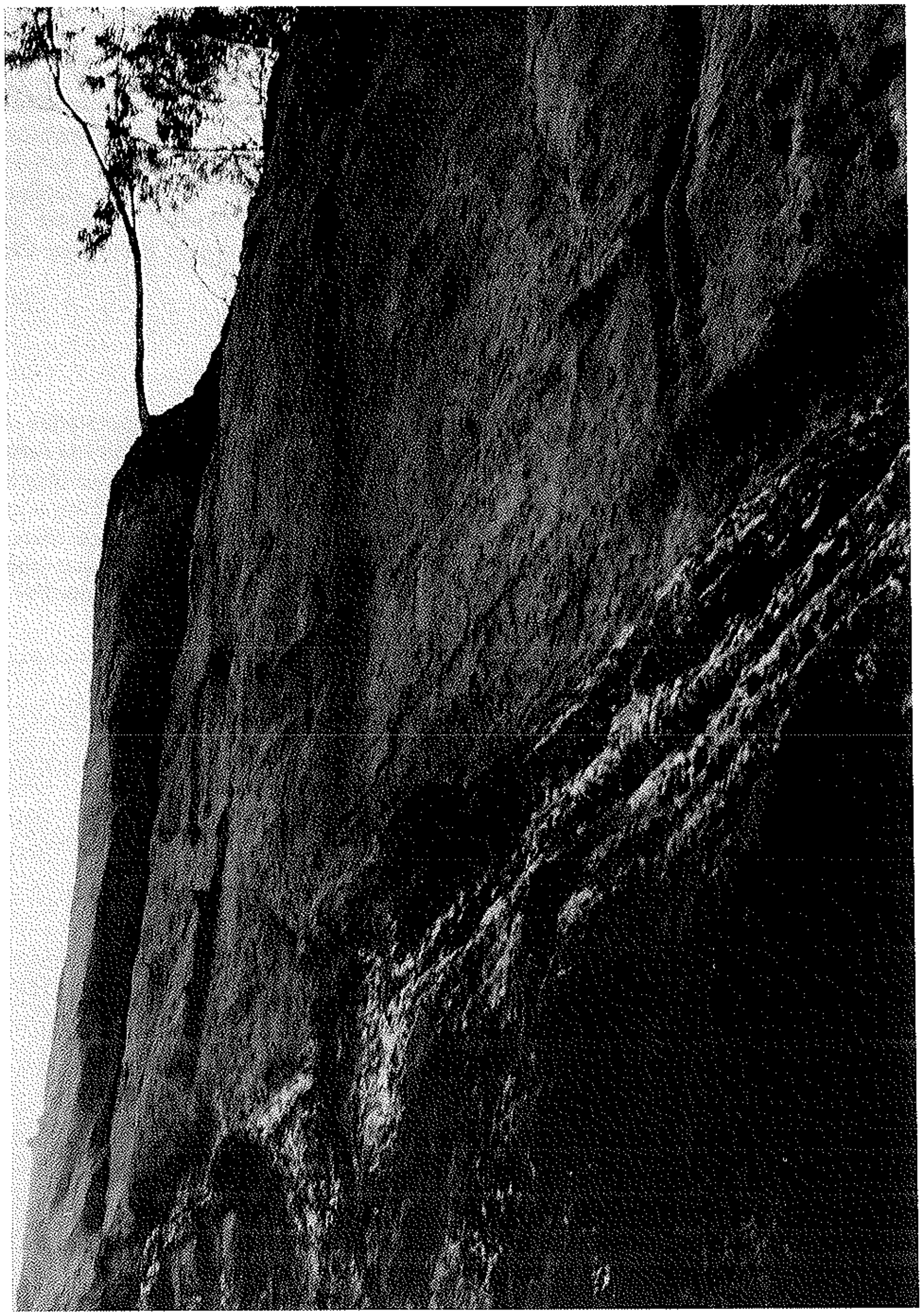


Figure 11. Vertical section of seacliff between Capitola and New Brighton where tree roots wedging themselves into joints parallel to cliff edge are causing failure of large blocks.

mation that are poorly to moderately indurated and vary considerably in resistance to wave erosion, and (2) unconsolidated sands and gravels of the Quaternary terrace deposits that are very erodable.

Cliff retreat here is caused primarily by surf action undercutting well-gapped master joints in the Purísima bedrock. The trend of these joints in conjunction with the prevailing direction of wave attack controls the trend of the coastline. Because these master joints are spaced at intervals from 2.5 to 6 m, cliff retreat is predominantly episodic. A given stretch of cliff will remain essentially unchanged for several years and then a section between joint sets will fail instantaneously. Other joints and faults that trend at a high angle to the seacliff are preferentially eroded, forming sea-caves which eventually collapse to form reentrants (Fig. 7a, 7b).

Cliff height could affect the erosion rate slightly if the failed material is coherent enough to protect the fresh cliff face from attack. Observations indicate, however, that this material is usually broken down within a few years.

A subordinate mechanism of cliff retreat occurs when the terrace deposits are stripped off the bedrock terrace by (1) surface runoff, (2) surf action (especially during storms), and (3) sloughing due to water saturation or some combination of the three (Fig. 8).

Rates of erosion vary considerably within the study area (Fig. 9, 10a, 10b) due to both natural and cultural factors. The primary natural factors are variations in exposure to wave attack, structure, stratigraphy and in some places cliff height. Human factors affecting erosion include placement of rip-rap, groins or other structures that buffer the cliff from wave attack or stop or impede the flow of littoral materials.

In the Opal Cliffs area various combinations of lithology, structure, and stratigraphy cause different rates of erosion on adjacent segments of seacliff. A series of faults that trend roughly perpendicular to the trend of the cliff have positioned, in the surf zone, beds of the Purisima Formation that vary considerably in their resistance to erosion. The resultant form of the cliff in plan shows a series of points and reentrants corresponding to the relatively resistant and

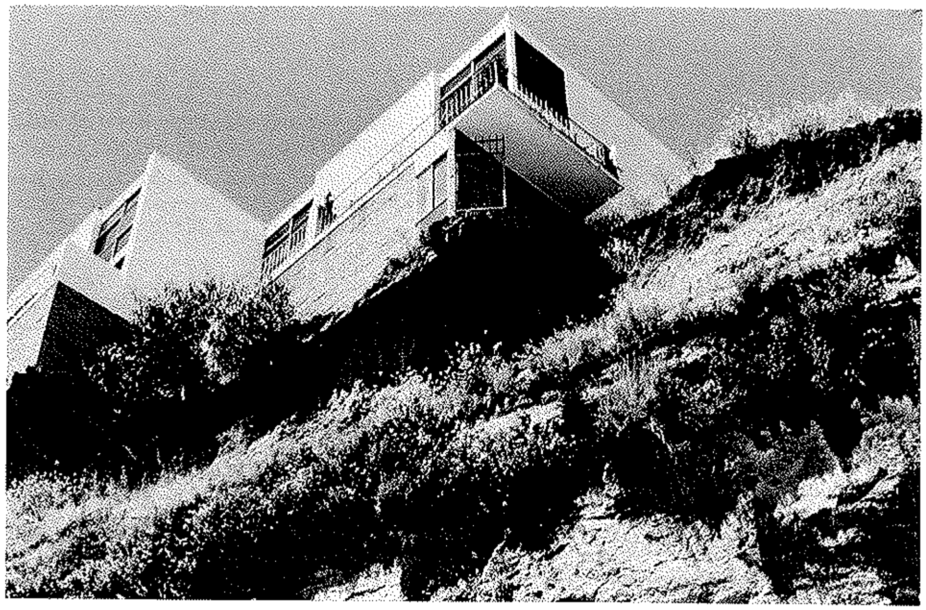


Figure 12. Apartments above beach at Capitola (see Figure 7a) which have been progressively undercut by continued seacliff erosion.

non-resistant beds exposed in the surf zone. In the area between Black Point and Corcoran Lagoon the terrace dips eastward under the surf zone exposing the highly erodable terrace deposits directly to wave attack (Fig. 9). This situation has engendered a high rate of cliff retreat in this area.

Changes in coastal erosion

Upcoast from the harbor. An immediate decline in cliff retreat from 12 to 42 cm/year on the average over the previous 110 years to 3 – 6 cm/year over the subsequent 10 years following harbor construction has occurred from the river mouth to the harbor (Figures 9, 10a, 10b). This stretch of coast is now protected by a wide sand beach. The little erosion still occurring is due to surface runoff, or human activity along the top of the bluff. Thus the serious recession of the bluffs here, which had destroyed parts of a road and was threatening houses, has virtually come to a halt.

Harbor to Soquel Point. The low bluffs immediately downcoast from the harbor have shown a decreased erosion rate since construction (Fig. 10b); the buildup of sand against the east jetty from littoral drift reversal and possibly the deposition of sand from dredging here may be responsible for increasing the size of the beach and offering more protection from wave attack. Proceeding towards Soquel Point, the net erosion rates have changed little since harbor construction; some areas show increases, some decreases (Fig. 10b). Where erosion has decreased, the emplacement of rip-rap has nearly always been the reason. At several points, erosion increased markedly (from 21 – 51 cm/year to over 80 cm/year) and then declined to less than 9 cm/year when riprap was put in.

Soquel Point to Capitola. Portions of this area also have shown declines in erosion rates since harbor completion (21 – 39 cm/year to 18 cm/year on the average), due primarily to protective riprap being emplaced. Where no protection was added, rates increased from 27 – 39 cm/year to 39 – 75 cm/year, a doubling in some places (Fig. 10b).

Downcoast from Capitola. Prior to harbor construction erosion rates here over the past 110 years averaged about 24 to 30 cm/year. The cliffs here are between 24 and 30 m high and bedrock joint sets trend both parallel to and at right angles to the coastline, making the rocks weak and prone to failure. Human intervention here has been extensive and has accelerated cliff retreat as well. The addition of water to the cliff edge, the load of traffic and construction, and the planting of trees whose roots have forced their way into the joints (Fig. 11) have weakened the cliffs. Average erosion rates have doubled or tripled to 90 cm/year in one area. An apartment complex on the cliff edge just each of Capitola beach has been undercut so that the entire corner of two apartments now extend over the cliff (Fig. 12). Another apartment next to this unit had to be removed due to undercutting. During the winter of 1971, a slab of cliff some 45 m long and 2 – 4 m wide crashed into the surf immediately to the east. This removed the cliff flush with the rear fence of one apartment and removed about half of the rear yard of an adjacent residence. Although the data indicate that erosion rates along this stretch of coast may have increased due to harbor construction, the rates must be considered in light of the episodic nature of cliff retreat and the relatively short time interval since harbor construction.

Conclusions

The San Lorenzo River contributes about 20 to 30 percent of the sand load in northern Monterey Bay whereas littoral drift from the open coast to the north provides the rest. The intrusion of two jetties into this system had significant effect on beach width and seacliff erosion both immediately upcoast and about 6 km downcoast. Cliff erosion upcoast was halted by the buildup of over 400,000 m^3 of sand against the west jetty. Downcoast beaches generally diminished in size, with the total disappearance of a major beach occuring at

Capitola as a result of jetty construction; a beach was subsequently rebuilt at considerable expense.

Sand buildup in the harbor during winter months has left the downcoast cliffs partially unprotected during the months of heaviest wave attack. Although certain sections of coast have now been protected by the emplacement of expensive rip-rap, the beach losses in many places accelerated an already rapid rate of cliff retreat. The sedimentary rock which compose the seacliffs are very erodible and are further weakened by joint sets and faults. Erosion which has undercut apartment houses, back yards, and roads is still occuring in places at accelerated rates.

The effects of harbor and jetty construction include: (1) the formation of a wide beach upcoast, (2) expensive annual sand dredging from the harbor mount, and (3) a loss of downcoast beaches followed either by increased cliff erosion rates or the emplacement of protective rip-rap.

REFERENCES

Anderson, R. G., 1971, Sand budget for Capitola Beach, California: U. S. Naval PostGraduate School, Monterey, Calif., unpub. M.S. Thesis, 60 p.

Feibusch, H., 1966, Preliminary study of beach depletion along the shoreline of the city of Capitola, California: Unpub. Rept. to City of Capitola, 12 p.

Moore, J. T., 1972, A case history of Santa Cruz Harbor California: Univ. California Hydr. Eng. Lab. Tech. Rept. HEL 24-14, 42 p.

Sayles, F. L., 1966, A reconnaissance heavy mineral study of Monterey Bay beach sediments: Univ. California Hydr. Eng. Lab. Tech. Rept. HEL-2-16, 20 p.

Shepard, F. P., Submarine geology: New York, Harper & Row, 557 p.

U. S. Army, Corp of Engineers, 1958, Survey report: Santa Cruz Harbor, California: U. S. Army Corps Eng., San Francisco Dist., 31 p.

———1969, City of Capitola, beach erosion study, Santa Cruz County, California: U. S. Army Corps. Eng., San Francisco Dist.

Wiegel, R. L., 1964, Oceanographical engineering: New York, Prentice-Hall, 532 p.

Wolf, S. C., 1970, Coastal currents and mass transport of surface sediments over the shelf regions of Monterey Bay, California: Marine Geol., v. 8, p. 321–336.

Yancey, T. E., 1968, Recent sediments of Monterey Bay, California: Univ. California Hydr. Eng. Lab. Tech. Rept. HEL-2-18, 145 p.

Yancey, T. E., and P. Wilde, 1971, Recent sediments of Monterey Bay—additional mineralogical data: Univ. California Hydr. Eng. Lab. Tech. Rept. HEL-2-33, 56 p.