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STUDIES ON THE GEOLOGY AND GEOLOGIC HAZARDS OF THE GREATER SAN DIEGO AREA, CALIFORNIA

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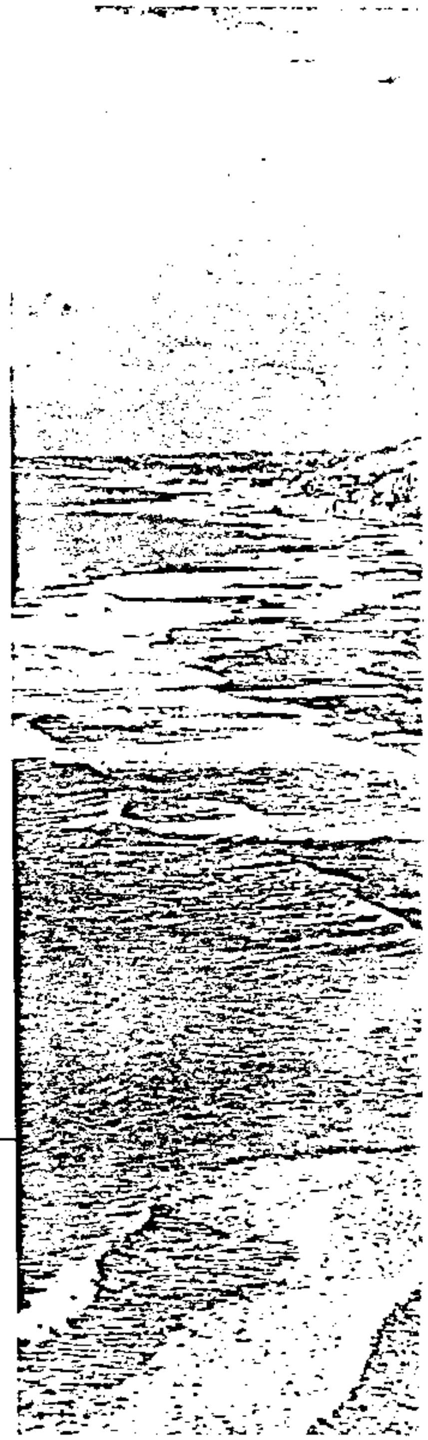

Torry Cliffs viewed from Scripps Institution of Oceanography. Type locality of the Scripps Formation (Eocene) is on the north wall of Black's Canyon, center right. Scripp's Submarine Canyon heads at lower left. Photo by George W. Moore, U. S. Geological Survey.

(Inman; R/CZ-3)

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BEACH AND CLIFF EROSION IN SAN DIEGO COUNTY, CALIFORNIA

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Aside from the esthetic and recreational uses of a natural sand beach, it also serves the important function of a barrier to the active erosion of the land. The presence of a sloping, porous, granular surface at the water-land interface acts as an efficient energy absorber for waves incident upon the land. Absence of this energy absorbing buffer along a shoreline often results in rapid shoreline retreat, with subsequent catastrophic effects on seafront property. Thus, an understanding of the basic physical processes responsible for the creation and maintainence of natural sand beaches is necessary in order to protect property from the geologic hazard of beach erosion.

Since the coastline of San Diego County is erosional in nature, the possibility of property damage by beach erosion is present whenever seafront property is developed. Numerous examples of serious beach erosion can be found from Oceanside south to Imperial Beach, indicating the regional nature of the problem. In some cases the erosion can be attributed to localized wave conditions, less resistant bedrock, or the presence of a man-made structure in the nearshore environment. However, it is becoming more apparent that the erosion is also related to the more general problem of the loss of the natural sand supply to the beaches.

LITTORAL PROCESSES IN SAN DIEGO COUNTY

Beaches in southern California, and specifically in San Diego County, can best be understood in terms of the littoral cell concept. A littoral cell is a segment of coastline that is involved in a complete cycle of littoral transportation and sedimentation (Inman and Frautschy, 1966). Under natural conditions a littoral cell is supplied with sediment by rivers and streams that empty into the ocean within its limits. The sandy material brought to the coast by fluvial action is then incorporated into a beach and transported along the coast by wave action. This longshore transport of sand is ultimately intercepted by a submarine canyon or other sink where it is diverted offshore and lost to the nearshore environment.

Two major littoral cells are recognized in San Diego County. The Oceanside littoral cell extends from Dana Point, in Orange County, south to the Scripps–La Jolla Submarine Canyon; the Silver Strand littoral cell extends from the mouth of the Tijuana River north to the entrance to San Diego Bay (Fig. 1). In both instances the littoral cell is characterized by a sandy beach along its entire length, and it is separated from adjacent cells by a rocky shoreline or short, intermittent beaches. Other beaches in the county include cove beaches such as those along the La Jolla and Point Loma headlands, and the Mission Beach spit across Mission Bay. These are small littoral cells having relatively local sources and sinks. They occur in indentations in the headlands where sufficient sand has been eroded from the bedrock to sustain a beach.

The Oceanside littoral cell includes 66 miles of coastline and is supplied with sediment by San Juan Creek in Orange County, the Santa Margarita, San Luis Rey, San Dieguito Rivers, and the San Onofre, Las Pulgas, Buena Vista, Agua Hedionda, San Marcos, Escondido, and Los Penasquitos Creeks. Langbein and Schumm (1958) showed that the annual sediment yield of a stream is related to the annual precipitation and its drainage area. Using this relationship, the total sand influx into this littoral cell can be estimated by summing the contribution from each river and stream. Thus, the total sand influx to the Oceanside cell from fluvial sources is estimated to have been about 590,000 cubic yards per year under previously existing natural conditions (Chamberlain 1960). However, many of these streams enter coastal lagoons that trap part of their sediment load; thus, the estimate of sediment contribution has been reduced to 350,000 yds^3/yr to account for lagoon sedimentation. The fluvial contribution is augmented by sand from cliff erosion, leakage from the adjacent northern littoral cell, and artificial placement of sand in the littoral environment by man. Quantitative estimates of the sand contribution to the Oceanside cell from these sources are nearly impossible, as little or no data exists for cliff erosion and leakage between cells, and the artificial input by man has been irregular and infrequent.

The Silver Strand littoral cell includes twelve miles of coastline, and has the Tijuana River as its natural sand source. Estimates based on the precipitation and drainage area indicate that the

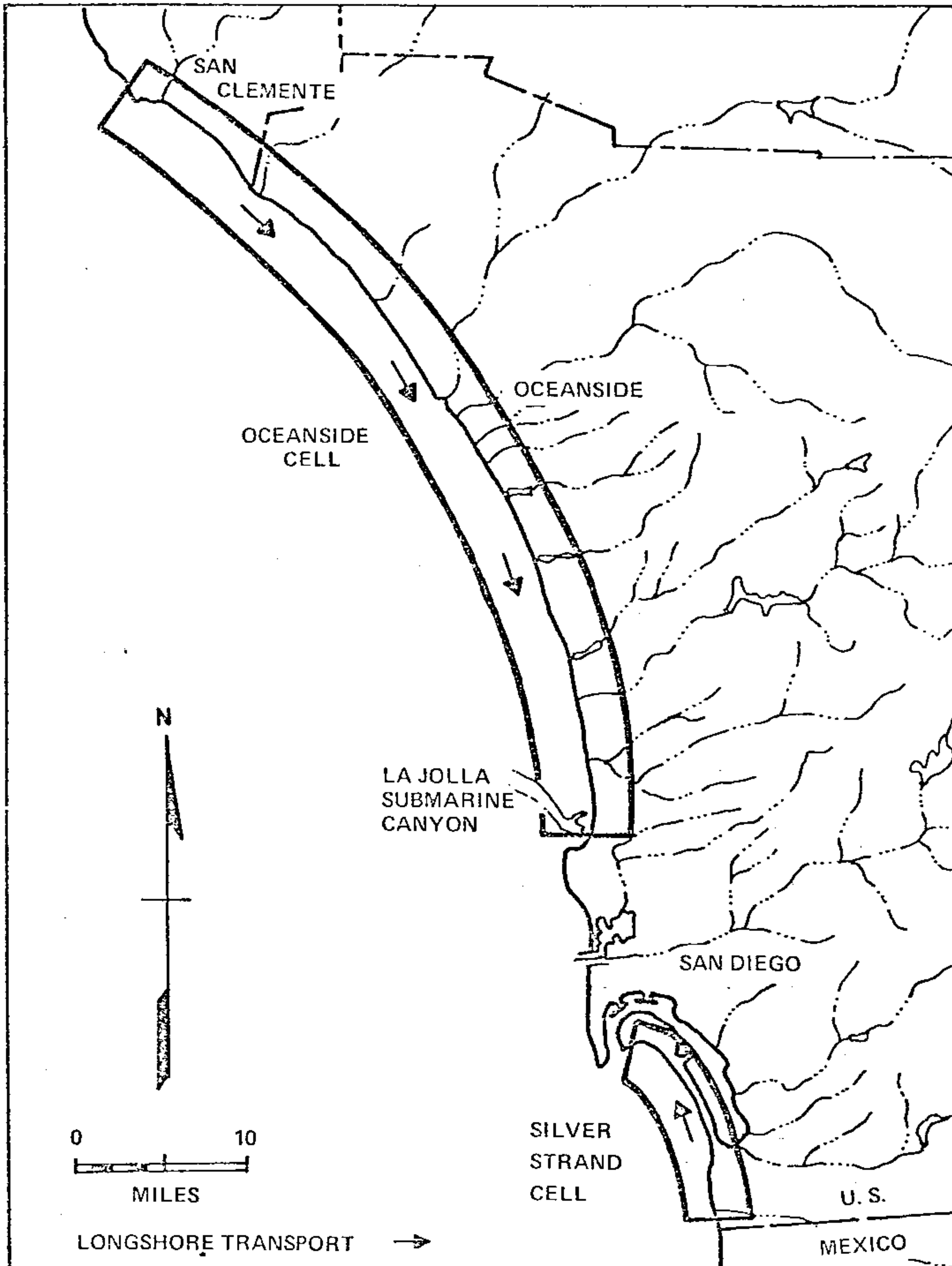

Figure 1. Littoral cells in San Diego County.

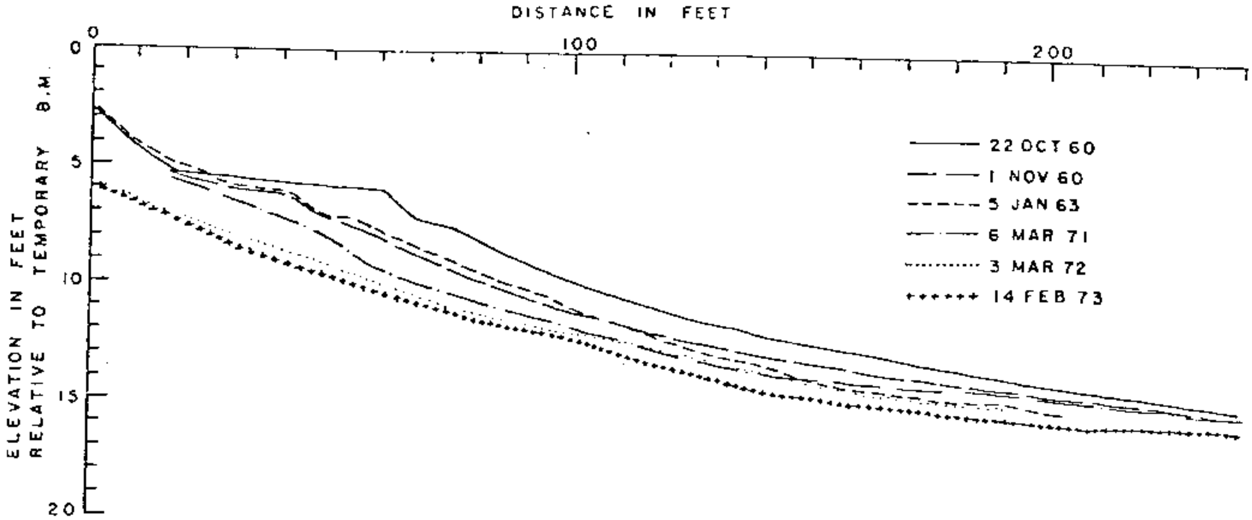

Figure 2. Beach profiles measured at Torrey Pines State Reserve. Rangeline is located at toll booth to northern park entrance. Elevations and distances are measured relative to a monument established on beach backshore. Profiles measured from 1960 to 1973 show the progressive decrease in sand level on the beach.

Tijuana River supplied about 660,000 cubic yards of sand per year to the coast under previously existing natural conditions. This sand supplies the Silver Strand littoral cell to the north and the Playas de Tijuana to the south. The only other source of sand to the Silver Strand cell has been artificial emplacement of sand on the strand from extensive dredgings in San Diego Bay.

Waves supply the energy to transport beach sand and to erode the shoreline in the absence of a beach. Longshore transport of sand is a result of a breaking wave placing the sand in motion and creating a longshore current that carries the sand load. Field measurements of the energy flux of waves and the resulting longshore transport of sand in the surf zone indicates that the longshore transport of sand is directly proportional to the longshore component of wave power (Inman and Bagnold, 1963; Inman, Komar and Bowen, 1969; Komar and Inman, 1970). Komar and Inman (1970) have determined that the immersed weight sand transport rate I_ℓ is related to the longshore component of wave energy flux P_ℓ as follows:

$$I_\ell = 0.77\,P_\ell$$

This relationship allows one to calculate the amount of sand that will be transported along a beach if the longshore component of wave power incident to the beach is known. In order to successfully apply this relationship, the wave energy incident to the beach must be measured. Calculations of the annual rates of sand transport requires that the budgets of wave energy be determined for each beach under consideration, and that the longshore component of wave power be calculated for all waves and directions in the sand budget. Since there are seasonal changes in the direction of wave approach, there will be similar changes in the direction of longshore transport, so that the net annual sand transport in a single direction is the difference between the sums of the downcoast and upcoast transports.

The budget of wave energy has not been measured in most cases so that the annual wave regime must be determined by hindcasting techniques using available weather information and wave records. Because this procedure has been performed for only a few sites on the San Diego County coastline, detailed wave data is not available for longshore power determination. However, as more wave data is measured along the county coastline, more precise determination of longshore sand transport can be made.

At present, the volume of longshore sand transport along the coastline is estimated from observed rates of erosion and accretion in the vicinity of coastal engineering structures and harbor entrances. Accretion and erosion caused by a structure in intercepting and trapping the sand being transported along the coast. Consequently, these transport rates are frequently underestimated when the structures are small, due to the inefficiency of the sand entrapment. The structures are then usually extended or changed in their configuration such that they become more efficient sand traps, thus trapping more sand and providing a better estimate of the total transport rate.

Estimates of longshore sand transport have been made on several beaches in San Diego County based upon the accretion-erosion effects of coastal structures. Longshore sand transport in the Oceanside littoral cell has been determined by the rates of sand entrapment at Oceanside Harbor and at Agua Hedionda Lagoon entrance channel. When originally constructed, the entrance to the present Oceanside Harbor entrapped 180,000 yds^3/yr of sand moving to the south (House Document 399, 1957). However, as the harbor was enlarged and the entrance jetties were extended, the amount of sand annually entrapped increased to approximately 340,000 yds^3/yr (San Diego Regional Water Quality Control Board Meeting, 15 December 1970). Five miles to the south a smaller jetty is used to maintain an entrance to Agua Hedionda Lagoon for a power plant discharge. Approximately 160,000 yds^3/yr of southward moving sand is entrapped by this entrance, based upon dredging records (Ritter, 1971). Thus, it appears that an average of 200,000 to 300,000 yds^3 of sand per year moves southward along the beaches in the Oceanside littoral cell.

Estimates of longshore sand transport in the Silver Strand littoral cell are based on erosion of dredge spoil placed on Silver Strand and the accretion of sand in the area off Zuniga Jetty. A total of 28,000,000 yds^3 of sand was placed as artificial fill along beaches in the Silver Strand cell between 1940 and 1946 from dredgings in San Diego Bay. A comparison of surveys made in 1946 and 1954 indicate that a total sand loss of 11,000,000 yds^3 from this beach took place during this period. Thus, an average sand loss of 1,400,000 yds^3/yr is indicated for this beach (Inman, 1973). A comparison of repeated beach profile surveys along Silver Strand show that about 1,000,000 yds^3/yr is being removed from the Silver Strand Beach (House Document 399, 1955). These measurements of sand loss from the beach and accretion off Zuniga Jetty indicate a net longshore transport of sand northward along Silver Strand Beach of about 1,400,000 yds^3/yr. This pronounced northerly longshore transport of sand is due to the exposure of Silver Strand Beach to waves approaching from a southerly direction, and protection of the beach from northerly waves by the Point Loma headland and Zuniga Jetty.

Using the principle of conservation of mass, with regard to sand in the littoral zone, an evaluation of the sources and agents of transport can be made. This procedure is referred to as the budget of sediment and consists of assessing the sedimentary contributions (credits) and losses (debits) and equating these in a given littoral cell (Inman and Frautschy, 1966). Using the available data, a sediment budget was determined for the Oceanside and Silver Strand littoral cells, as shown in Table 1. The Oceanside cell, under natural conditions, would have a sand supply of about 350,000 yds^3/yr from the streams entering the cell. As stated previously, the net longshore transport by waves in the cell is at least 250,000 yds^3/yr to the south. This sand is intercepted by the heads of Scripps and La Jolla Submarine Canyons and is transported through the canyon to deep water at a rate of 260,000 yds^3/yr (Chamberlain, 1960). Thus, it appears as though the Oceanside littoral cell was in an equilibrium condition with an adequate sediment supply and a balanced sediment budget.

The Silver Strand littoral cell under natural conditions had a sand supply of 660,000 yds^3/yr from the Tijuana River. A net longshore transport to the north of at least 1,400,000 yds^3/yr is indicated from the erosion on Silver Strand Beach. This sand is apparently diverted offshore by Zuniga Jetty and by tidal currents in the entrance to San Diego Bay, where it is being deposited over a relatively large area offshore. A comparison of surveys made in 1923 and 1934 of this offshore area indicate that approximately 2,000,000 yds^3/yr of sand is being deposited in the offshore area (Chamberlain, Horrer and Inman, 1958). The budget of sediment for the Silver Strand littoral cell under natural conditions is somewhat out of balance, as the Tijuana River does not supply a sufficient quantity of sand

Table 1. Budget of sediment for San Diego County littoral cells under natural conditions *(numbers 1 and 2) and under present conditions **(numbers 3 and 4)

TOTAL SEDIMENT SUPPLY TO CELL "CREDIT" yds^3/yr	NET LONGSHORE TRANSPORT yds^3/yr - DIRECTION	TOTAL SEDIMENT LOSS FROM CELL "Debit" yds^3/yr
1. OCEANSIDE CELL 350,000	250,000 - South	260,000
2. SILVER STRAND CELL 660,000	1,400,000 - North	2,000,000
3. OCEANSIDE CELL 230,000	250,000 - South	260,000
4. SILVER STRAND CELL 180,000	1,400,000 - North	2,000,000

*Sources of the quantities listed in this table are given in text.

**This table reflects the reduced sediment supply caused by sediment entrapment due to dams in coastal drainage basins.

Table 2. Modification of Principal Southern California Coastal Streams (from Norris, 1964)

Name of Drainage Basin	Number of Dams	Basin Area Sq. Miles	Area of Basin Blocked	Percentage of Basin Blocked by Dams
A. OCEANSIDE CELL:				
Orange Co. Coastal Group	0	193	0	0.0
San Juan Creek	0	274	0	0.0
San Onofre Creek	0	350	0	0.0
Santa Margarita River	3	741	319	43.0
San Luis Rey River	2	557	206	36.9
Batequitos Goup Buena Vista Creek Agua Hedionda Creek San Marcos Creek	1	320	100	31.2
San Dieguito River	4	327	304	93.2
Los Penasquitos Creek	0	172	0	0.0
TOTAL	10	2819	929	32.9
B. EMBAYED COASTLINE:				
Rose Canyon Group	0	72	0	0.0
San Diego River	3	435	277	66.0
Sweetwater River	2	181	150	83.3
Otay River	2	140	99	70.7
TOTAL	7	828	526	63.5
C. SILVER STRAND CELL:				
Tijuana River	4	1645	1175	72.5
TOTAL	4	1645	1175	72.5

for the available longshore power. Consequently, this littoral cell, under natural conditioning is in a state of disequilibrium, and the maintenance of a continuous wide beach along Silver Strand is not possible. This disequilibrium was indicated by the fact that there was a very narrow Silver Strand and a narrow beach at Coronado before 1900. When man started to modify Silver Strand with groins and jetties, and began to artificially supply sand to the littoral cell from dredging spoil the beach attained its present configuration.

MODIFICATION OF THE NATURAL SYSTEM

The discussion of littoral processes in San Diego County to this point has considered only a natural system with no modification by man. However, to be meaningful to the present situation, an assessment of the effects of man on this natural situation must be given along with the implications of these modifications. Perhaps the most serious and least obvious modification to the natural system is the termination of the natural sand supply to the littoral cells by the damming of coastal streams for water reclaimation and flood control. A dam placed on a stream course is an effective barrier to water flow, but it is also a total barrier to sediment transport. Thus, a dam severs the sediment producing drainage basin from the coastline.

Table 2 is from Norris (1964) and shows the effect of damming the coastal streams in San Diego County. This data indicates that about 33% of the sand supply to the Oceanside littoral cell is severed from the coast by dams, so that of the 350,000 yds^3/yr potentially available in the natural system only 230,000 yds^3/yr can still reach the coastline. Thus, the apparent surplus in sand supply to the Oceanside cell does not exist, and with the limited precipitation in the area in recent years the littoral cell is deficient in sand. Figure 2 shows the progressive depletion of sand on Torrey Pines Beach in the Oceanside littoral cell during the last 12 years. As can be seen, the average sand level on this beach has steadily decreased over this period, with the beach now about three feet lower than in 1960.

Table 2 also shows a similar situation with respect to the Silver Strand littoral cell, where damming has severed 72% of the sand supply from the coastline. In this case, the 660,000 yds^3/yr natural sand supply is reduced to 180,000 yds^3/yr, which is insufficient to maintain Silver Strand Beach. The problem of insufficient sand supply is already apparent at the south end of the cell where the community of Imperial Beach is undergoing beach erosion. This erosion has progressed over the last few years to the point that protective and sand entrapment structures have been installed. These structures have not been successful and erosion has progressed as far north as Silver Strand State Beach. Serious erosion at the northern end of the littoral cell has been forstalled by artificial replenishment with dredge spoil sand placed on the beach near the Navy base south of Coronado. This artificial source of sand has widened the beach at Coronado and actually isolated former shore protection structures from the ocean. However, it did not benefit the southern end of the littoral cell where beach erosion is most acute.

Since the available data indicate that the littoral cells in San Diego County are now experiencing a shortage of sand, it is apparent that beach erosion is going to become an increasingly prevalent problem. As the sand presently in transit is transported through the cell and ultimately lost, the wave energy will eventually dissipate in active erosion of the sea cliffs. This will result in the cliffs receding much more rapidly than at present. Thus, much of the San Diego County coastline will be similar to the resistant headland areas of La Jolla and Point Loma but without the benefit of resistant bedrock. This will be a serious problem, since sea cliff recession rates of up to 1.5 ft/yr have been measured in the unconsolidated alluvium at Scripps Institution of Oceanography (Shepard and Grant, 1947). Recognition of this future situation is important for rational planning within the coastal zone. Such planning will necessarily involve: 1) proper location and set-back of sea front structures from the shoreline; 2) proper design and construction of protective measures necessary for existing structures; 3) consideration of proposed dams and flood control channels that involve coastal drainage basins in terms of sediment supply to the coastline; 4) consideration of artificial replenishment of beach sand by nearshore disposal of sand dredge spoil and sand construction spoil; and, 5) innovative research and development into procedures for recycling beach sand through the littoral cell rather than continue to allow its loss from the nearshore environment.

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