Title
Budget of Sediment and Prediction of the Future State of the Coast

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BUDGET OF SEDIMENT AND PREDICTION OF THE FUTURE STATE OF THE COAST

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 9

BUDGET OF SEDIMENT AND PREDICTION OF THE FUTURE STATE OF THE COAST

9.1 LITTORAL CELLS AND THE BUDGET OF SEDIMENT

For purposes of this study, the coast of the San Diego Region is divided into three segments consisting of two littoral cells and one "group" of littoral cells and subcells (Figure 9-1). The two well-defined littoral cells are the Oceanside Littoral Cell to the north and the Silver Strand Littoral Cell to the south. The Mission Bay Group of Subcells is located between the Oceanside and Silver Strand Cells, and extends from Point La Jolla to Point Loma. For convenience, this group will be referred to here as the Mission Bay Littoral Cell.

Division of the coast of the San Diego Region into three relatively large segments provides for a continuous, uninterrupted series of subcells and cells without the problem of having gaps in coastal coverage or of having separate general descriptions for the many subcells. This chapter provides a detailed description of the three littoral cells, a budget of sediment for each cell, and a long-term prognosis for the beaches, cliffs, and lagoons contained therein.

These cells were first described by Inman in 1960, at which time simple budgets were derived emphasizing rivers as sediment sources, beaches as transport paths, and submarine canyons as sinks (Inman & Chamberlain, 1960; Inman & Frautschy, 1965). Following the early studies, advances in the understanding of sediment dynamics led to the development of more refined budgets by a number of different investigators (e.g., California, 1977a; 1977b). As indicated in Table 9-1, most of the effort was concentrated on the Oceanside Cell.

Prior to the Coast of California Storm and Tidal Waves Study (CCSTWS), the advances in evaluating the budget of sediment resulted from: (1) the development and evaluation of models for the longshore transport of sediment (i.e., Inman, 1968; Komar & Inman, 1070; Kraus & Harikai, 1983; White & Inman 1989), and (2) the quantification of seasonal changes in beach profiles (Nordstrom & Inman, 1975; Winant, et al., 1975; Pawka, et al., 1976).

Starting from the knowledge acquired during these earlier studies, the research conducted under the auspices of CCSTWS has

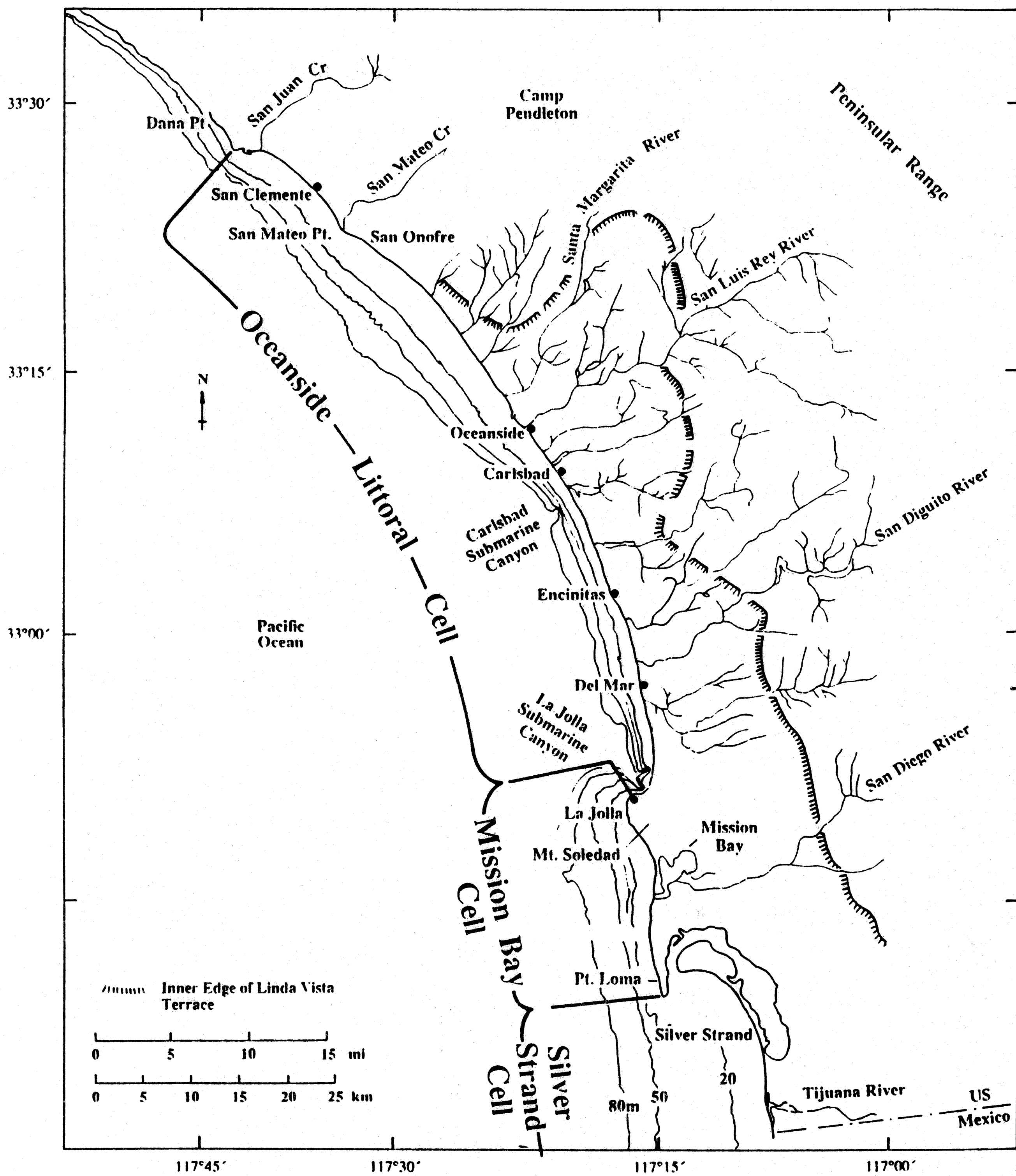

Figure 9-1. Location and principal physiographic features of the Oceanside, Mission Bay, and Silver Strand Littoral Cells (20, 50, 80 m equal 66, 164, 262 ft) (from Inman, 1983).

TABLE 9-1
LIST OF SEDIMENT BUDGET ANALYSES
SAN DIEGO REGION

Reference	Littoral Cell: Oceanside	Mission Bay	Silver Strand
Chamberlain, Horrer & Inman (1958)			X
Inman & Chamberlain (1960) (S. California cells defined)	X		
Inman & Frautschy (1965)	X		
Inman (1973)			X
Nordstrom & Inman (1973)	X		X
Inman, et al. (1974)			X
Inman (1976; reissued 1980)	X		X
Hales (1978)	X		
Inman & Jenkins (1983)	X		
Weggel & Clark (1983)	X		
Inman, et al. (1986: CCSTWS 86-1)	X	X	X
Everts (1987: CCSTWS 87-3)			X
Sonu (1987: CCSTWS 87-4)	X		
Everts & Bertolotti (1988: CCSTWS 88-7)		X	
Everts (1990: CCSTWS 90-2)	X		

added significantly to our understanding of the budget of sediment. The most important concepts that have emerged from the CCSTWS studies are: (1) the magnitude of the sediment yield from erosion of coastal blufflands in contrast to that from rivers; (2) the effect of cluster storms and other high "total-energy" type storms in causing downwelling transport of material from the shorezone onto the shelf; (3) the extent of downwelling as documented by historical changes in beach profile and by deposition of material on the shelf in depths of 10 to 40 m (30 to 130 ft); and (4) the importance of changes in wave climate on transport paths in the shorezone. All four of these findings are new and need to be tested with rigor. If they are correct, as they appear to be, they have enhanced our understanding of coastal processes to the extent that the analyses presented in Sections 9.6 to 9.8 represent the first in a new generation of sediment budgets.

There are a number of apparent anomalies and contradictions in the data set that must be resolved before proceeding with estimates of the budget of sediment. These include: (a) extensive offshore deposition along the 10 fathom (18 m) contour, (b) the relative stability during the past decade of the volume of sand on the beach down to the depth of 30 feet, c) the apparent stability of the shoreline, with slight average accretion, (d) high rates of cliff erosion, and (e) a reduction in the yield of sand due to trapping behind dams on rivers. A stable shorezone (b, c) appears to be inconsistent with a diminished supply of sand from the traditional river source (e), and extensive offshore accretion (a). These apparent contradictions must also be evaluated from the standpoint that they occur on a collision coast (see Section 9.2) which, with its narrow shelf and seacliffs, is customarily an eroding coast.

9.2 GEOLOGIC SETTING

9.2.1 Tectonics

Plate tectonics, or the movement of oceanic plates and adjacent continental masses, determines the type of coastal zone and its exposure to waves and currents. The west coasts of the Americas are collision coasts, occurring along a plate margin where two plates are in collision or impinging upon each other. These coasts are characterized by narrow continental shelves bordered by deep basins and ocean trenches. Submarine canyons cut across the narrow shelves and enter deep water. The shore is backed by sea cliffs and coastal mountain ranges; earthquakes and volcanism are common. Although now a northward moving terrain associated with the San Andreas fault, the San Diego Region retains most of the characteristics of its collision history.

In contrast, the eastern coasts of the Americas are examples of mature trailing-edge coasts that move with the plate and are situated upon the stable portion of the plate away from the plate margins. These coasts typically have broad continental shelves that slope into deeper water without a bordering trench. The coastal plain is also typically wide and low-lying, containing lagoons and barrier islands.

The Oceanside Littoral Cell is typical of a collision coast having a narrow shelf, terrestrial sources of sediment, submarine canyons, and downwelling over the shelf. The Mission Bay Littoral Cell, however, is a river mouth embayment confined between two headlands (Point La Jolla and Point Loma). The Silver Strand Littoral Cell is a complex bifurcated system with northward transport in the U.S. portion of the cell associated with a spit-built embayment (San Diego Bay) and shelter from winds and waves by Point Loma.

The characteristics of the continental shelf in these three cells determine the processes and paths of sediment transport. The "shelf break" or "shelf edge" that marks the outer edge of the continental shelf occurs at a depth of about 80 m (262 ft) off the entire coast of southern California (Shepard, 1963). The shelf to 80 m depth is narrow throughout the Oceanside Littoral Cell, wider at Mission Bay and widest off the Silver Strand (Table 9-2). The slopes of the shelf are correspondingly steeper moving from the southern to northern cell. Where the shelf slope exceeds the critical equilibrium slope for onshore wave transport, material on the shelf will not be transported to the shorezone. Consequently, coastal downwelling and transport down submarine canyons are important paths for the Oceanside Littoral Cell but are not important for the Mission Bay and Silver Strand Littoral Cells.

9.2.2 Sealevel Change

Sealevel changes associated with global climatic cycles during the Pleistocene and Holocene have influenced the position and physiography of the coast. A generalized sealevel curve applicable to the southern California coast during the past 30,000 years is shown in Figure 9-2. Sealevel rose rapidly, about 1 m per century, from 18,000 years BP (before present) to about 10,000 years BP, followed by a more gradual rise of about 10-12 cm per century from 6,000 BP to present. Sealevel continues to rise, and projected increases in the rate of sealevel rise are discussed in Chapters 4 and 8 and Section 9.3.

The position of mean sealevel relative to onshore topography influences sediment transport and coastal landforms (Inman, 1983). Stream and valley cutting were most extreme during the sealevel minimum of 21,000 years (18,000 radiocarbon years) BP (Figure 9-3). Huge volumes of sediment and large size material were moved to the

TABLE 9-2
SLOPES AND WIDTHS OF THE SHELF[a]
SAN DIEGO REGION

Location		Depth Range (m)				
		0-10	0-20	20-50	50-80	0-80
Camp Pendleton	Distance, km	1.2	2.8	2.3	1.6	6.7
5 km N of Harbor	Slope, %	0.8	0.7	1.3	1.9	1.2
Solana Beach	Distance, km	0.75	1.25	1.5	1.25	4.0
15 km N of Pt La Jolla	Slope, %	1.3	1.6	2.0	2.4	2.0
Mission Bay	Distance, km	0.8	1.4	2.7	4.1	8.2
2 km N of Jetties	Slope, %	1.2	1.4	1.1	0.7	1.0
Silver Strand	Distance, km	0.35	4.2	7.6	3.7	15.5
8 km N of Border	Slope, %	2.8	0.5	0.4	0.8	0.5

[a] Shelf break is at 80 m (262 ft)

Source: U. S. Geological Survey, Topographic-Bathymetric N1 11-8 (Santa Ana) and N1 11-11 (San Diego) from Inman, et al. (1993).

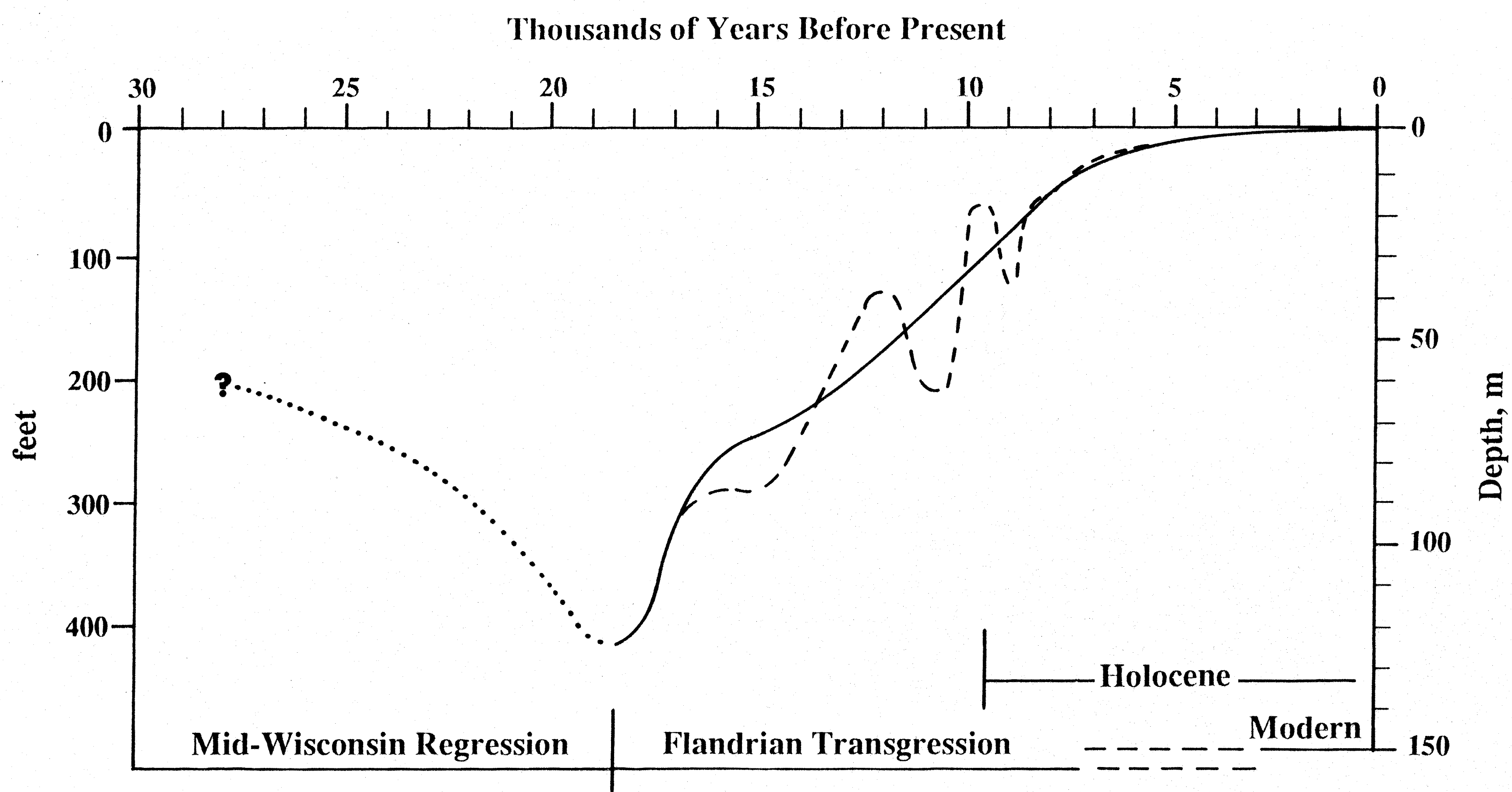

Figure 9-2. Late Quaternary fluctuations in sealevel. Solid line is the "generalized" sealevel curve (from Curray, 1965): dashed line is detailed curve (from Curray 1960, 1961). Tree ring and Uranium/Thorium dates give greater age than the radiocarbon ages for these curves. Recent studies indicate the glacial maximum was 21,000 ($^{230}Th/^{234}U$) years BP with a sealevel lowering of 121 ± 5 m (400 ± 16 ft) (Fairbanks, 1989; Bard, et al., 1990).

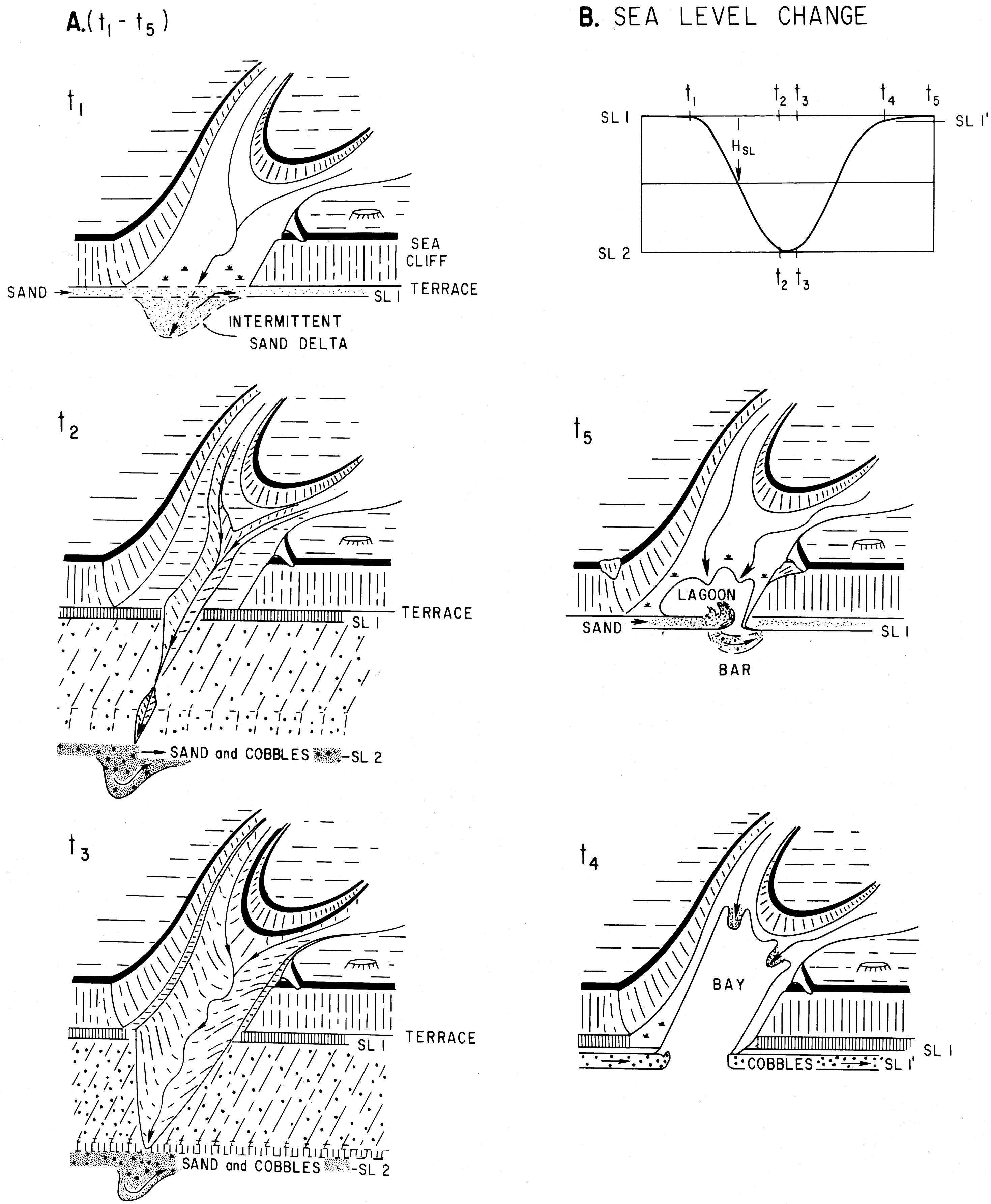

Figure 9-3. (A) Schematic diagram for valley cutting during lowered sealevel and bay-trapping of sediment during sealevel rise. (B) Assumed sealevel curve for times t_1 - t_5 (from Inman, 1983).

coast. Deep valleys were cut across the exposed continental shelf. As sealevel rose during the Flandrian transgression, these valleys flooded and lagoons flourished along the coastline. Table 9-3 lists the coastal wetlands of the San Diego Region. According to the San Diego Museum of Natural History, salt marshes covered over 32,000 acres of twelve ecologically diverse coastal wetlands in 1900. By 1990, less than 3,000 acres remain due to human intervention.

Shelf Deposits

The continental shelf has been cut and molded by wave action during the many marine transgressions of the Pleistocene glacial period. Older sediments of Tertiary (3-70 million years ago) through Cretaceous (70-135 million years ago) age outcrop in many places along the shelves of the San Diego region. Most thick deposits on the shelf are associated with fill of stream valleys cut across the shelf during lowered sealevel (Figure 9-3), with shore parallel zones of fill associated with marine terrace cutting and sea cliff formation by waves, and with fill along fault displacements on the shelf (Figure 9-4).

The volumes of the Holocene (past 10,000 years) deposits along the shelf, based on seismic reflection studies, are given by Fischer, et al. (1983) and the volumes of specific nearshore deposits by Osborne, et al. (1983). Estimates of the Holocene volumes on the shelves of the San Diego Region are given in Table 9-4. The Flandrian transgression has resulted in a relatively thin veneer of sand over the older, wave-cut surface of the shelf. Generally, this veneer of modern to Holocene material does not exceed a thickness of 1 to 3 m (3 to 10 ft) (e.g., Fischer, et al., 1983; Tekmarine, 1988: CCSTWS 88-5).

One of the significant discoveries of the CCSTWS effort is the band of accretion at depths of about 18 m (60 ft) in the Oceanside Littoral Cell. The initial analysis by Dolan, et al. (1987) and the more detailed study by Everts (1990: CCSTWS 90-2) indicate that between the hydrographic surveys of 1934 and 1971/72, sediment accreted in a band along the 10-fathom contour of the Oceanside cell (Figure 9-4). (Note: Because the term "10 fathom contour" has appeared extensively in the literature, it is used instead of its equivalent in SI units.) The net accretion of sand size material for the 84 km (52 mi) length of the Oceanside littoral cell is estimated by Everts (ibid.) to be about 27 million cubic meters (35 x 10^6 cy), or 322 m^3 per m of beach (385 cy/yd) (Table 9-5). If this finding is correct, and it appears to be, it provides valuable information about transport of sediment to the shelf during modern times.

The shore-parallel deposition along the Oceanside shelf (Figure 9-4) appears to be associated with the 10-fathom terrace and

TABLE 9-3
COASTAL WETLANDS OF THE SAN DIEGO REGION

Location	Watershed mi^2	Wetland or Marsh acres	Estuary or Lagoon acres	Volume of Sand[a] $10^6 m^3$	10^6cy
San Mateo Creek	132	30			
San Onofre Creek	30	2			
Las Flores Creek	20	60			
Santa Margarita River	740		268	2.1	2.8
San Luis Rey River	558		40	0.5	0.6
Buena Vista Lagoon	20		220		
Agua Hedionda Lagoon	29		400		
Batiquitos Lagoon	53		600	6.9	9.0
San Elijo Lagoon	77		530	6.9	9.0
San Dieguito Lagoon	350		300	1-8	2-10
San Dieguito River					
Los Peñasquitos Lagoon	98		630	2.1	2.8
Mission Bay	53		4,600		
Kendall-Marsh		21			
Famosa Slough		31			
San Diego River	440	300		0.4	0.5
San Diego Bay	415	11,130			
Sweetwater River				1.4	1.8
Tijuana Estuary	1,730		1,320		

[a] Estimated potential sand sources (Environmental Task Force, 1970)

Source: State Coastal Conservancy (1989)

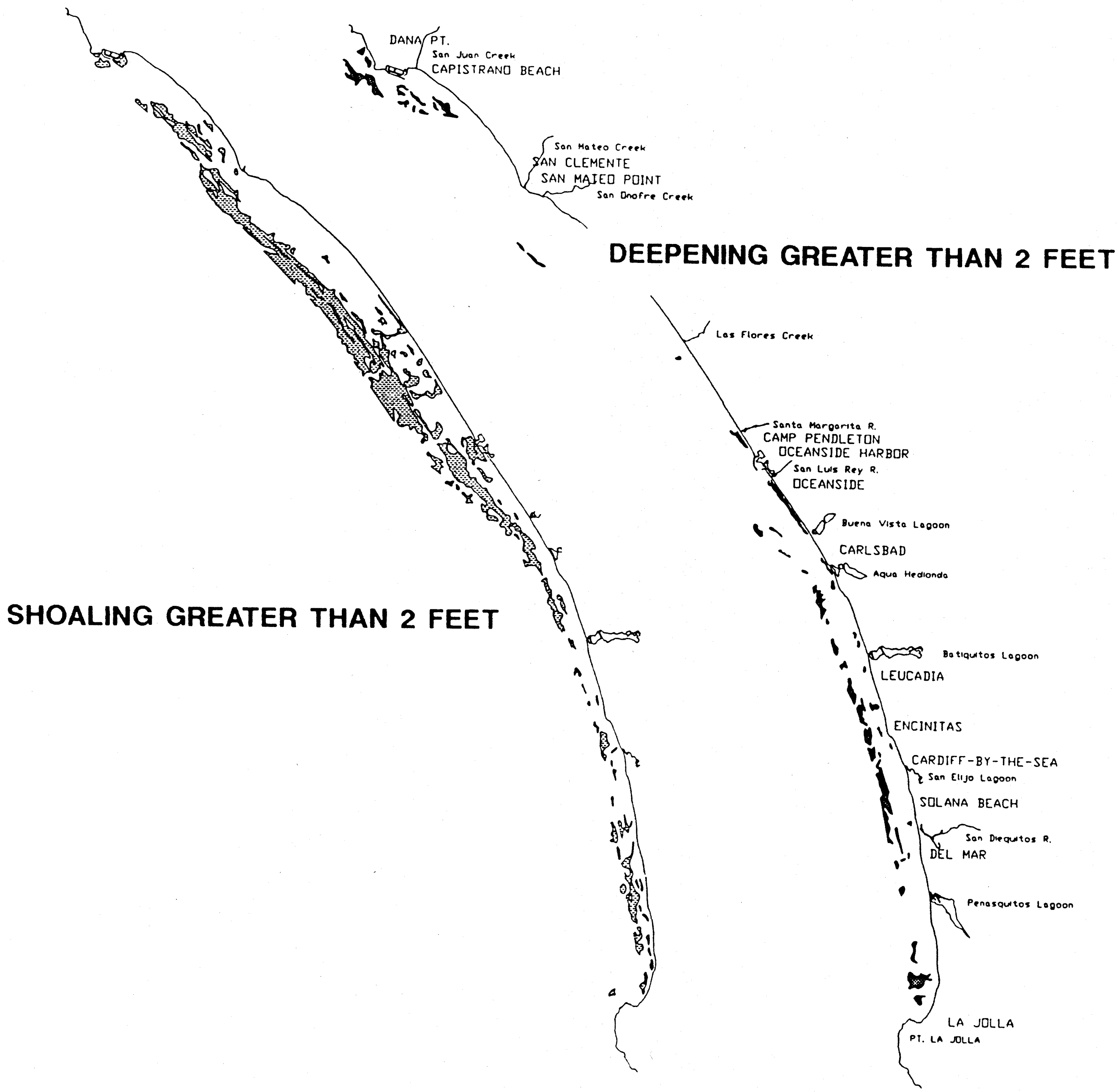

Figure 9-4. Regions of shoaling and deepening on the continental shelf of the Oceanside Littoral Cell from comparison of the NOAA hydrographic surveys of 1934 with those of 1970/71. The survey error was found to be ± 2 ft = 60 cm (from Everts, 1990; CCSTWS 90-2).

TABLE 9-4
VOLUME OF HOLOCENE SEDIMENT ON THE CONTINENTAL SHELF
SAN DIEGO REGION

Coastal Reach (Length)	Depth Interval on Shelf: 0-30 m, Volume 10^6 m^3	Depth Interval on Shelf: 0-30 m, Volume/ unit length of coast 10^3 m^3/m	Depth Interval on Shelf: 0-100 m, Volume 10^6 m^3	Depth Interval on Shelf: 0-100 m, Volume/ unit length of coast 10^3 m^3/m
Dana Point to San Mateo Pt. (14 km)	124.8	8.9	401.4	28.7
San Mateo Pt. to Oceanside Harbor (27 km)	156.2	5.8	711.5	26.4
Oceanside Harbor to Carlsbad Sub. Cyn. (11 km)	83.7	7.6	198.1	18.0
Dana Point to Carlsbad Sub. Cyn. (52 km)	364.7	7.0	1311.0	25.2
Carlsbad Sub. Cyn. to Point La Jolla (32 km)	89.6	2.8	288.6	9.0
Dana Point to Point La Jolla (84 km)	454.3	5.4	1599.6	19.0
Point La Jolla to Point Loma (22 km)	6.3	0.3	319.6	14.5
Point Loma to US/ Mexico Border (22 km)	57.1	2.6	196.0	8.9

Source: Fischer, et al. (1983), Figure 20.

TABLE 9-5
SHELF ACCRETION OF SAND-SIZED SEDIMENT
BETWEEN NOAA SURVEYS OF 1934 AND 1971/72
OCEANSIDE LITTORAL CELL

	Depth Interval (feet) and Volume (yd^3)			Rate (12-120 ft)	
Shoreline Reach	12-60	60-120	12-120	yd^3/yd-yr	m^3/m-yr
Dana Point to San Mateo Point[a]	1,909,000	243,000	2,152,000	3.9	3.2
San Mateo Point to Carlsbad Sub. Canyon[b]	17,999,000	6,487,000	24,486,000	16.0	13.3
Carlsbad Sub. Canyon to Point La Jolla[c]	5,570,000	3,041,000	8,611,000	6.6	5.5
Total[d]	25,478,000	9,771,000	35,249,000	10.4	8.7

[a] Shoreline distance 14 km (8.5 mi)

[b] Shoreline distance 38 km (23.5 mi)

[c] Shoreline distance 32 km (20.0 mi)

[d] Shoreline distance 84 km (52 mi)

Source: Everts (1990: CCSTWS 90-2)

faulting (e.g., Osborne, et al., 1983, plate XIV-D). The shelf slopes increase from 0.7% to 1.3% at the 20 m (66 ft) depth contour off Oceanside (Table 9-2). The probable cause of this deposition is discussed in more detail in Section 9.4.

A careful analysis of the two surveys (Everts, 1990: CCSTWS 90-2) along the Oceanside shelf indicates a survey error of about ± 60 cm (± 2 ft) as shown in Figure 9-4. Inspection of profiles across the shelf (e.g., Figures 9-10 and 9-15) shows that shelf slopes are steepest at the shorerise where erosion occurred and at the 10-fathom terrace where accretion occurred. These findings cannot be explained by systematic horizontal or vertical errors, and the longshore coherence of the accretion and erosion zones rule out random error.

In contrast to the Oceanside shelf, that off Mission Bay shows a net erosion in depths of 10 fathoms (18 m) and greater off Mission Bay and a net deposition off Point La Jolla and Point Loma (Figure 9-5). This pattern of erosion and deposition is interpreted to result from a net northerly transport along the shelves off Mission Bay and the Silver Strand with deposition at the headlands of Point La Jolla and Point Loma. The severe southerly waves and winds associated with the 1939 tropical storm may have driven this transport, as discussed under Section 9.3. It seems likely that sediment was also removed from depths less than 10 fathoms off Mission Bay and Silver Strand, but this material has been replaced by seasonal transport in the shorezone.

9.2.3 Terrigenous Sources of Sediment

The relative contributions of the major sources of sediment to the littoral zone have changed with sealevel fluctuations associated with the last Pleistocene glacial maximum (circa 21,000 years BP) and subsequent transgression. Figure 9-6 provides a schematic interpretation of the two major sources, rivers and streams versus blufflands and seacliffs.

Major streams and rivers possessed the maximum potential for sediment transport and land erosion during the sealevel minimum of 21,000 years BP. All else being equal, the transport capacity of a stream is proportional to its slope raised to the 3/2 power. At the maximum sealevel regression of approximately 120 m (390 ft), streams and rivers would have transported more and larger materials to the coast. They would also have cut upland valleys and deep valleys across the now-submerged shelf (Inman, 1983).

Seacliffs and coastal blufflands became more important sources as sealevel rose during the Flandrian transgression. The short stillstand between 10,000 and 8,000 years BP cut the 10-fathom terrace into the shelf, and the sea cliff associated with this terrace contributed sediment to the littoral zone. But the major injection of sediment from the seacliffs and associated blufflands

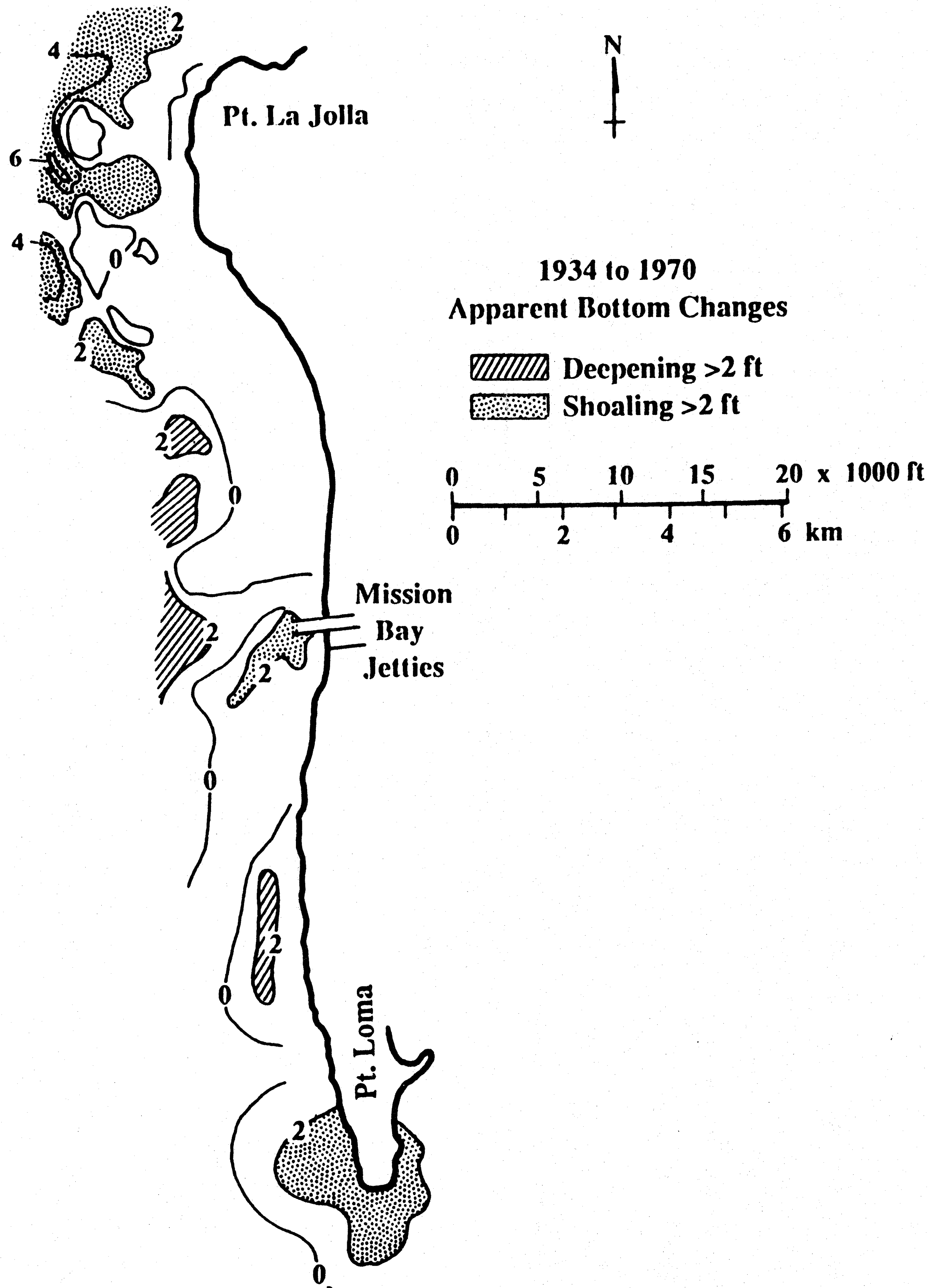

Figure 9-5. Changes in bathymetry between NOAA hydrographic surveys of 1934 and 1970 for the Mission Bay Littoral Cell (after Everts & Bertolotti, 1988: CCSTWS 88-7).

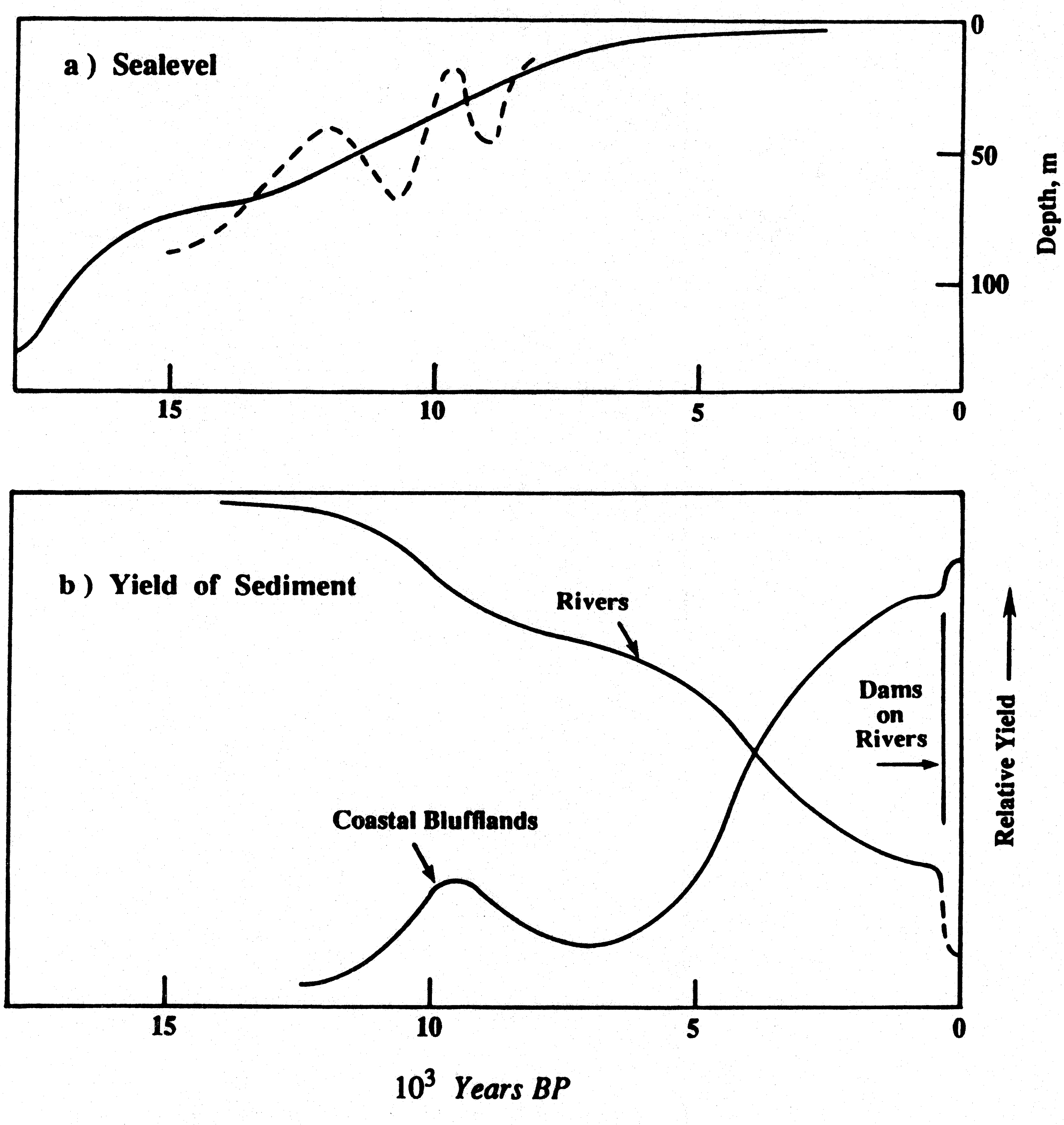

Figure 9-6. Schematic diagram of the influence of sealevel rise (a) on the relative yield of sediment to the shorezone (b) by rivers and coastal blufflands.

occurred when sealevel approached its present position approximately 4,000 years BP (Figure 9-2). Erosion of the seacliffs progressed by means of wave notching at the base of the cliff, followed by failure and collapse of the entire face of the sea cliff.

During the period between 4,000 years BP and the present, weathering and gullying of the blufflands associated with the tall, vertical seacliffs has created localized high relief. A slower rate of sea cliff retreat as the platform widened provided the time necessary for the gullying to transform the coastal terraces behind the seacliffs into coastal badlands. Evidence that the numerous small coastal canyons are features of the past 4-5,000 years also comes from the prehistoric Indian sites of coastal San Diego County. At sites dating to 6-8,000 years BP, midden deposits and burials are exposed by small transecting canyons that open onto the beach (Masters, 1985). During the historic period and continuing at present, urban and agricultural activities have accelerated blufflands erosion (see Inman & Brush, 1973).

As the coastal blufflands have evolved, the rivers and stream valleys traversing the coastal plain have filled with sediment and lost transport potential due to the concurrent rise in sealevel. Only major floods (e.g., 1916, 1938, 1939, 1980, 1983) will now break through the valley fills and create large deltas at the river mouths. Compounding this natural reduction in transport capacity has been the construction of dams which has vastly diminished the amount of river-borne sediment delivered to the coast (Inman, 1985).

In consequence, the contribution of coastal blufflands as a sediment source to the littoral zone has increased, while the contribution of rivers and streams has decreased. The yields of sand and gravel from rivers and streams in the San Diego Region for both natural and present conditions are listed in Table 9-7. The relative importance of the yields from rivers versus coastal blufflands is given by comparison of Tables 9-6 and 9-7. It should be noted here that the blufflands' yield is based on comparison of the USC&GS topographic surveys of 1889 with the US Geological Survey quadrangle surveys of 1968. These sources have different scales, and the early surveys provide no vertical datum information and steep slopes are shown by hachure marks. In consequence, the estimates of bluffland yields should be regarded as approximate.

Unfortunately, there is a wide disparity in the estimates of river yield. The variability in estimates is partly due to a lack of agreement in calculating bedload (Inman & Jenkins, 1983) and to the intermittent nature of floods which bring most of the material to the sea. In particular, the Santa Margarita River appears to

TABLE 9-6
YIELD OF SANDY SEDIMENTS FROM COASTAL BLUFFLANDS
(COASTAL TERRACES, GULLIES, SLUMPS)
1889-1968[a]

Coastal Section	Sea cliff Height (MSL)		Sea cliff Erosion[b]		Total Yield of Sediment		% Coarser than	Total Yield Sandy Sediments		Yield Rate Sandy Sediments	
	m	ft	cm/ yr	ft/ yr	10^6 m^3	10^6 yd^3	62.5µ	10^6 m^3	10^6 yd^3	m^3/ m–yr	yd^3/ yd-yr
San Onofre Park[c]	27	90	6	0.20	15.2	19.9	72	10.9	14.3	18.1	21.7
Camp Pendleton[d]	18	60	8	0.25	13.2	17.2	54	7.1	9.3	11.8	14.1
Torrey Pines Park[e]	15-80	50-260	3	0.10	7.9	10.3	42	3.3	4.4	6.9	8.4

[a] Data from Kuhn, et al. (1988: CCSTWS 88-8).

[b] Data from Everts (1990: CCSTWS 90-2).

[c] Length of coastal reach 7620 m (8330 yd); width 455-685 m (500-750 yd).

[d] Length of coastal reach 7620 m (8330 yd); width 1140 m (1250 yd).

[e] Length of coastal reach 5940 m (6500 yd); width 1140 m (1250 yd).

TABLE 9-7
YIELD OF SAND AND GRAVEL FROM RIVERS AND LARGE STREAMS
SAN DIEGO REGION

River	Source	Natural[a] 10^3 m^3/yr	Present[b] 10^3 m^3/yr
San Juan Creek	Inman & Jenkins, 1983	37	30
	Brownlie & Taylor, 1981		
	California, 1977b	43	29
	Simon, Li & Assoc, 1988		
San Mateo and San Onofre Creeks	Inman & Jenkins, 1983	30	15
	Brownlie & Taylor, 1981		
	California, 1977b		28
	Simon, Li & Assoc, 1988		
Santa Margarita River	Inman & Jenkins, 1983	22	18
	Brownlie & Taylor, 1981	17	14
	California, 1977b	15	
	Simon, Li & Assoc, 1988		
San Luis Rey River	Inman & Jenkins, 1983	86	28
	Brownlie & Taylor, 1981		
	California, 1977b		
	Simon, Li & Assoc, 1988		
San Dieguito River	Inman & Jenkins, 1983	53	5
	Brownlie & Taylor, 1981	32	3
	California, 1977b		4
	Simon, Li & Assoc, 1988		
San Diego River	Brownlie & Taylor, 1981	35[c]	8
	Simon, Li & Assoc, 1988		
	California, 1977b		110
Tijuana River	Brownlie & Taylor, 1981	105	52
	Inman, 1976	535	
	Everts, 1987	153-380	100-115
	This study	200	50

[a] Pre-dam conditions

[b] Estimates for present, post-dam conditions

[c] Average 35,000 m^3/yr; range 11,700 to 58,300 m^3/yr; largest event 157,000 m^3

be a larger contributor than estimated by most investigators (e.g., Simons, Li & Associates, 1988: CCSTWS 88-3). The deep stream valley cut beneath the present coastline during the Holocene suggests that the Santa Margarita had a higher yield of sediment than did the San Luis Rey in former times. Seismic studies show the Santa Margarita was excavated to a depth of over 45 m (150 ft) below present sealevel at the coast whereas the San Luis Rey was cut about 30 m (100 ft) deep at the present shoreline (Osborne, et al., 1983, Plate XIV-D). Also, aerial photographs archived at Scripps Institution of Oceanography show significant sand deltas off the Santa Margarita River mouth in March 1952, January 1953 and January 1966.

9.3 WEATHER, WAVES AND EXTREME EVENTS

Along the southern California coast, there are decades of relatively stable, mild weather interrupted by shorter periods of severe storms. The most recent period of mild weather occurred during the 30 years between the mid-1940's and mid-1970's. Winters were moderate with low rainfall. Winds were moderate and predominantly from the west-northwest. The principal wave energy was from Aleutian lows having storm tracks which usually did not reach southern California. Summers were mild and dry with principal wave energy coming from the southern hemisphere. During the summer and fall, no tropical storms reached the west coast.

We now appear to have entered a period of more variable climate having a larger number of extreme weather events. Some years have remained mild; others have been relatively severe. For example, the winter of 1976/77 was mild and dry because the storm tracks missed the southwestern coast. The winter of 1977/78 was much wetter, with flooding along the west coast. The winter of 1978/79 was mild, as were the winters of 1980/81 and 1981/82. In contrast, coastal flooding occurred during the winters of 1979/80 and 1982/83 when Aleutian storm tracks traveled far to the south before approaching the west coast from the west-southwest. These storms caused the worst coastal flooding in southern California history. Summaries of the beach erosion and damage associated with the winter storms of 1979/80 and 1982/83 are given in National Research Council (1982) and Dean, et al. (1984).

During the 19th century, there was a similar pattern of alternating periods of drought and wet weather. A wet period appears to have occurred from about 1830 to 1841, followed by drought from 1842 to 1883. The subsequent wet period, 1884-1891, was so intense that it has been remembered as "Noah's Deluge."

9.3.1 Wave Climate

The wave climate is the prevailing set of wave conditions incident to a particular coastal segment averaged over an extended period of time (typically several years to several decades). The wave climate includes swell from distant storms as well as local wind waves. It is presented as a data set consisting of the variables wave height, period and direction. These variables are averaged over the period of interest and reported in terms of their frequency of annual occurrence. The wave climate is commonly divided into seasons such as winter, summer and transitional. When used for calculating the longshore transport of sand, the wave climate yields the estimated (potential) transport for a typical year within the averaged time range.

During the long periods of mild, stable weather, the wave statistics for exposed coast in the Southern California Bight vary seasonally in response to winter storms from the Gulf of Alaska and subtropical cyclone or southern hemisphere swell in summer (see Chapter 4 for a detailed discussion of deep-water waves). According to spectral studies (Pawka, et al., 1976; Seymour, 1980), winter waves typically have a net energy flux component to the south because they are generated by North Pacific storms passing close to southern California. Summer waves, on the other hand, often show a net energy flux to the north from more distant storm sources off the coast of Mexico or from South Pacific waters. Therefore, the annual wave energy flux affecting the littoral drift is the net of two competing seasonal sources. The overall climatic trends of the Pacific basin determine which of these wave sources will dominate the wave climate in the San Diego Region for any particular year.

Comparing observations of Sverdrup & Munk (1947), Wiegel (1956), Pawka, et al. (1976), and Seymour, et al. (1980), wave statistics have varied from year to year, and this variability has accompanied a shift in characteristic weather patterns over the past 45 years. The mild period from 1945 until 1977 was maintained by a strong high pressure ridge that prevented subtropical cyclones from tracking near enough to southern California to have a dominant effect on the waves (Inman & Jenkins, 1983). Consequently, swell from the North Pacific storms dominated this period, causing a net littoral drift to the south as evidenced in the skewness of sand spits, fillet beaches and lagoon entrances toward the south. The 1945-1977 drought was ended by the wet period 1978-1983, with the pronounced El Niño events of the winters of 1979/80 and 1982/83. The moisture in this transitional wet period (and the preceding one of 1934-1945) came from subtropical cyclones advancing up from the south and from Aleutian storms tracking far to the south before approaching the west coast from the west-southwest. The wind waves due to these violent west-southwesterly storms cause reversal of the net littoral drift, shifting sand spits and reopening the natural lagoon inlets to the north. Because the transitional wet periods are brief in comparison to the protracted droughts, the long-term net littoral drift is still to the south.

Recent events suggest that wave statistics based on the mild 1945-1977 period may prove to be anomalously low in wave intensity and erroneous in wave direction (Seymour, et al., 1984; Inman, et al., 1986). Addressing the unusual weather across the United States in recent years, Karl, et al. (1984) find statistically (Monte Carlo simulation) that the return period of occurrence is 1164 years. They conclude that "the recent variability is either a moderately rare event in a reasonably stationary climate, or it represents climate change."

Reviews of wave climate in the Southern California Bight are given by Walker, et al. (1984) and Moffatt & Nichol (1989: CCSTWS 88-6). They summarized the 30 storms producing the highest waves during the period 1900 to 1983. This list is updated in Table 9Ä8 to include data for the period December 1982 through December 1988 from Begg Rock Buoy reported in the monthly records of the Coastal Data Information Program (CDIP). Begg Rock Buoy records unsheltered deepwater wave data representative of the open waters of the Southern California Bight and began recording 20 October 1982. Recent studies (O'Reilly, 1989) show that wave heights in the vicinity of Begg Rock may be enhanced over true deepwater heights by wave refraction and diffraction.

Table 9-8 gives an ordered list of 41 wave events during the 89 year period of this century in which the significant wave heights in unsheltered deepwater were 4.0 m (13.1 ft) or greater. The data are also plotted in Figure 9-7. It is interesting that 26 (63%) of these wave events occurred during the 9 years of the 1980's. Undoubtedly, inclusion of the data from Begg Rock Buoy has biased the statistics toward greater numbers in recent years. In previous years, island sheltering diminished the intensity of many deepwater waves to the 4 to 5 m (13 to 16 ft) range, causing them to be omitted from the list of hindcast events. If waves are high enough, however, they will be recorded as high wave events even within the sheltered waters of the Bight. Consequently, the bias toward greater numbers of high wave events in recent years should decrease with increasing intensity of the unsheltered waves.

There are 17 wave events with wave heights of 5 m (16.4 ft) and greater, and 7 (41%) occurred in the last 9 years (Table 9-8). There are 8 events greater than 6 m (19.7 ft), and 6 (17%) occurred in the last 9 years. As can be seen in Figure 9-7, these data support an intensification of the wave climate during the 1980's. There also appears to be a southerly shift in the storm tracks and an increase in the meridional (north-south) alignment of extratropical cold fronts as compared with the previous zonal

TABLE 9-8
UNSHELTERED DEEP-WATER WAVES ($H_S \geq 4$ m)
IN THE SOUTHERN CALIFORNIA BIGHT, 1900 THROUGH 1988

Date	Significant Wave Height m	(feet)	Wave Period sec	Direction[a] degrees true	Source[a]
17 Jan 88	10.1	(33.2)	14-17	280	CDIP[b]
Sep 39[c]	8.2	(26.9)	14	205	MA
Apr 58	7.7	(25.1)	8-18	290	PWA
Mar 83	7.3	(23.6)	11-19	265	PWA
Jan 81	6.6	(21.5)	6-16	270	PWA
3 Dec 85	6.5	(21.4)	14-18		CDIP
Jan 83	6.4	(21.0)	8-21	285	PWA
Nov 82	6.2	(20.4)	12-15	295	PWA
Feb 63	5.9	(19.5)	10-14	270	PWA
Jan 78	5.7	(18.6)	7-17	285	PWA
Feb 60	5.6	(18.3)	11-19	295	PWA
Jan 58	5.5	(18.1)	9-14	270	PWA
Mar 04	5.5	(17.9)	12	225	MA
Mar 12	5.3	(17.5)	12	270	MA
Feb 83	5.2	(17.1)	16-17	275	PWA
Feb 15	5.0	(16.5)	12	280	MA
Jan 15	5.0	(16.3)	12	205	MA
Jan 43	4.9	(16.2)	11	180	MA
Jan 53	4.9	(16.0)	15-19	260	MA
1 Dec 82	4.8	(15.8)	8-14		CDIP
23 Dec 82	4.8	(15.8)	6-12		CDIP
Feb 69	4.8	(15.6)	8-15	285	PWA
Feb 80	4.8	(15.6)	9-15	255	PWA
13 Mar 87	4.8	(15.6)	18-22		CDIP
Jan 81	4.7	(15.4)	17-18	265	PWA
31 Jan 87	4.7	(15.4)	10-12		CDIP
13 Dec 84	4.6	(14.9)	10-14		CDIP
Dec 69	4.4	(14.4)	20-21	275	PWA
27 Mar 88	4.4	(14.5)	10-12		CDIP
10 Dec 83	4.4	(14.3)	14-16		CDIP
4 Dec 83	4.4	(14.3)	12-16		CDIP
16 Dec 82	4.3	(14.2)	12-18		CDIP
Jan 16	4.3	(14.0)	10	250	MA
4 Nov 84	4.3	(14.0)	14-16		CDIP
9 Mar 84	4.2	(13.9)	18-22		CDIP
22 Dec 88	4.2	(13.9)	14-18		CDIP
16 Jan 88	4.2	(13.8)	14-18		CDIP
18 Nov 83	4.2	(13.7)	14-16		CDIP
15 Jan 87	4.1	(13.3)	10-12		CDIP
22 Dec 87	4.0	(13.3)	8-10		CDIP
11 Nov 83	4.0	(13.2)	12-14		CDIP

[a] Directional data hindcast to points outside the islands(Figure 3.7, sites 12, 13, 22) from Walker et al. (1984) updated by Moffatt & Nichol (1988). CDIP data for 1983-88 from Begg Rock Buoy (Figure 3.7, site 13). CDIP, Coastal Data Information Program; MA, Marine Advisers (1961); PWA, Pacific Weather Analysis (1983).

[b] 17 January 1988 data also from Seymour (1989) and O'Reilly (1989).

[c] Tropical Storm (Horrer, 1950).

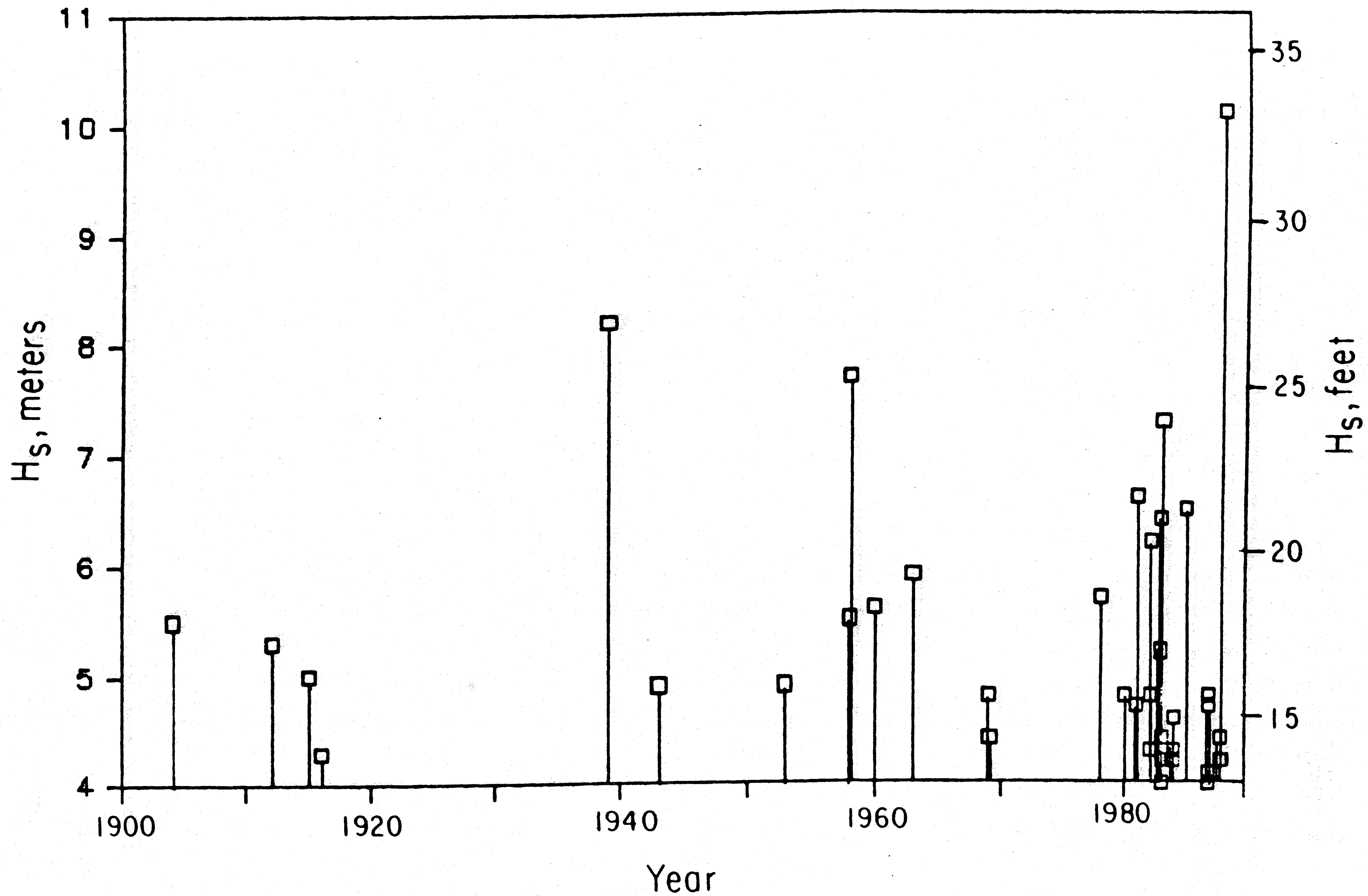

Figure 9-7. Occurrence of wave events with significant deep-water heights, $H_s \geq 4$ m (13.1 ft), in the unsheltered waters in the vicinity of Begg Rock in the Southern California Bight. Data from Table 9-8.

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(east-west) alignment (S.A. Jenkins, 1990, personal communication). These changes appear to decrease the magnitude of the net southerly transport potential of the waves.

However, the apparent shift in the wave climate needs to be quantified in greater detail by analysis of historical data. The measurements of Pawka, et al. (1976) and Seymour, et al. (1980) do not extend over sufficiently long periods of time to answer questions of longer term climatic effects on the wave climate and net littoral drift. For the present purpose of analyzing the budget of sediment, the apparent shift cannot be ignored.

Estimates of the Potential Longshore Transport

As the wave climate in the Southern California Bight changed beginning with the ENSO (El Niño-Southern Oscillation) years of 1979/80 and 1982/83, the prevailing northwesterly winter waves have been replaced by waves approaching from the west, and the previous southern hemisphere swell waves of summer have been replaced by tropical storm waves from the waters off Central America. The net result appears to be a decrease in the southerly component of the net longshore transport of sand that prevailed during the preceding 30 years.

The potential longshore transport of sand as determined from wave arrays in shallow water off San Clemente, San Onofre and Oceanside for the period July 1983 through December 1989 is shown in Figure 9-8. The up- and down-coast (northerly and southerly) components of longshore transport are approximately equal during this 6.5 year period. In interpreting this figure, it is noted that the net transport is the difference between two large components. Inman & Jenkins (1983, Table 3.3.2) show that the net southerly transport of 194,000 m^3/yr (254,000 yd^3/yr) estimated to occur at Oceanside for the 24 year period 1951-1974 was only 18% of the sum of the up- and down-coast transports. Further, most of this transport could be accounted for by local wind waves from the then prevailing northwesterly sea breeze waves. Because of the relatively short period of the sea breeze waves, much of their energy is not recorded on the wave arrays, which are located at depths of about 10 m (33 ft). In addition, an uncertainty of as little as 2^o in the orientation of the wave arrays would change the direction of the estimated net longshore transport. Under these conditions, it is estimated that the net longshore transport of sand during the period from 1983 to 1989 is about 50,000 m^3/yr (65,000 yd^3/yr) to the south in the vicinity of Oceanside.

9.3.2 Extreme Events

For the San Diego Region, the processes causing beach erosion and damage to coastal structures have been addressed in Chapters 4 and 8. Short-term processes such as tides, storms, and ENSO

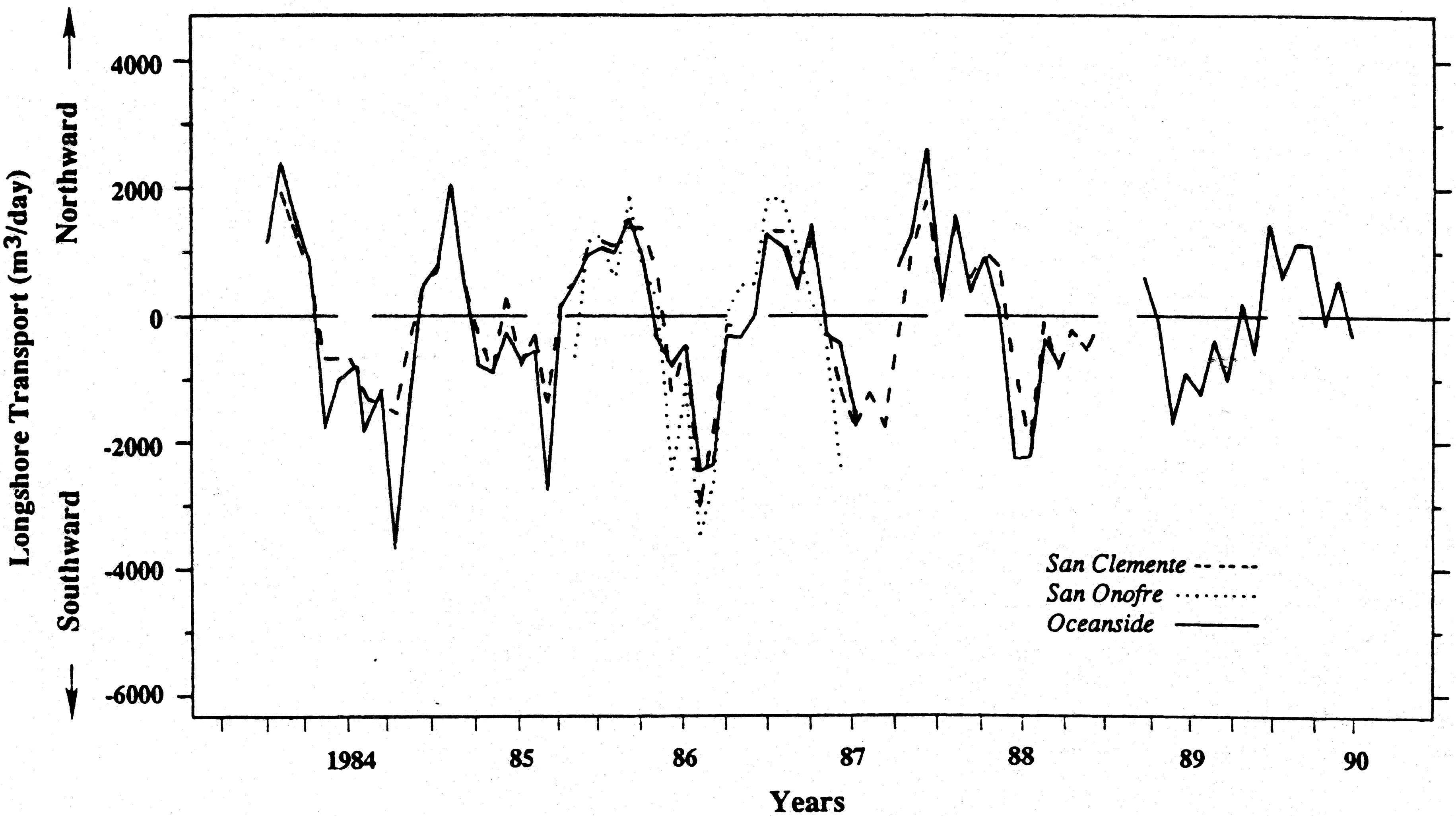

Figure 9-8. Estimates of the potential longshore transport rate of sand from wave arrays at stations indicated. Estimates based on equation (5-33) with K_ℓ = 0.8 (from Elwany, et al., 1990).

(El Niño-Southern Oscillation) events are the best understood and have statistical databases for predicting future recurrence intervals. Long-term processes such as global warming and subsidence (both natural and induced) have as yet unknown trends and large uncertainties. Extreme events of low probability in the San Diego Region include earthquakes and tsunamis.

Tides

Tides cause the greatest changes in water levels along the southern California coast (see extensive discussion in Chapter 4; Moffatt & Nichol, 1989: CCSTWS 88-6), and tidal range can reach 3 m (10 ft) at San Diego. During the next decade, years with predicted extreme tides are 1990-1991, 1994-1995, and 1999-2000. Exceedences of sea level over the predicted tide result from El Niño episodes and storm surge and waves. During the extreme winter of 1982-1983, these effects raised the water level approximately 30 cm (1 ft) at the tide gage locations at San Diego. The coincidence of extreme high tides with high waves will produce extensive damage to coastal structures and seacliffs, but high tides alone will have little effect on beach profiles.

Storms

The largest waves to reach southern California are generated by either eastern north Pacific tropical cyclones or extratropical storms resulting from warm or cold fronts in the North Pacific (Section 4.5). One of the largest significant deepwater wave heights hindcast to be 8.2 m (26.9 ft) with a period of 14-17 seconds occurred during a tropical storm on 25 September 1939 (Table 9-8). The largest waves ever measured in the Southern California Bight were produced during 17-18 January 1988 by an extratropical storm. Wave intensity peaked in the evening of 17 January with a maximum unsheltered, deepwater significant wave height of 10.1 m (33.2 ft) and a period of 14-17 seconds at Begg Rock (Table 9-8). Storm surge increased water levels in the Los Angeles area about 25 cm (0.8 ft) above predicted tides.

Single extreme events like the two storms described above have significant design implications for coastal structures, but they may not be the most destructive to beaches. The importance of storm clusters was discussed in Section 8.4. Such clustering, as occurred in 1982-1983, may cause erosion of the beach profile past the point at which sediment yield during drought periods can effect recovery.

The frequency of occurrence of the storm clusters is unknown, but it may be about once or twice per century. Early meteorological records are accurate only in terms of temperature and rainfall, and most rainy years are not associated with storm clusters. The only explicit nineteenth century descriptions of these storms along the coast of southern California are those of Richard Henry Dana covering the years 1834 through 1836. Prior to the well-documented events of 1979-1980 and 1982-1983, early reports imply that storm clusters occurred in the 1890's and again in the 1920's.

Another means by which a single storm can wreak extensive erosion is to increase its total energy by prolonged blow. The Atlantic coast storm of March 1989 was one of the three highest total-energy storms for the period 1942 through 1989. Although the maximum deepwater significant wave height was only 5 m, waves 1.5 m and greater occurred for 115 hours, producing a total- energy of 11.5 MWh/m (megawatt hours per meter) of beach (Dolan, et al., 1990).

Comparison of Storms of September 1939 and January 1988

These two storms, separated by almost 50 years, were the two maximum intensity storms of the century. The January 1988 storm with deepwater, unsheltered significant wave heights of 10.1 m (33.2 ft) was more intense, but of shorter duration, than the September 1939 storm which had hindcast deepwater significant waves of 8.7 m (28.5 ft) (Horrer, 1950). Both made landfall with strong coastal winds in the Southern California Bight, and both had peak energy in period ranges of about 14-17 sec. Calculations indicate that in deepwater the 1939 storm produced waves with a total-energy of about 12 MWh/m (megawatt hours per meter of storm front) whereas the 1988 storm had a slightly lower total energy of about 10 MWh/m.

Comparison of measured and predicted (hindcast) waves during the 1988 storm showed that there was a much more rapid rate of increase in wave height than predicted (Seymour, 1989; O'Reilly, 1989). It is likely that the 1939 storm also had higher waves than hindcast, but there were no wave measuring stations for comparison at that time.

However, the effect of island sheltering produced a maximum attenuation of the easterly traveling 1988 storm and a minimum attenuation for the northerly traveling 1939 storm. Thus the 1939 storm was far more intense at the shoreline and had much greater total-energy along the coast of the San Diego Region. Most of the total-energy of 12 MWh/m of the 1939 storm was expended directly on the coast. In contrast, data obtained at CDIP wave arrays off San Clemente, Oceanside, Del Mar, and Mission Beach show that the 1988 storm's total-energy was reduced to less than 1 MWh/m at the coast.

These calculations explain why the 1988 storm had little long-term effect on the beaches of the San Diego Region. Beach profiles were measured along many ranges within 10 days following the storm. Comparison of these profiles with those prior to the storm shows that the profiles were eroded to depths of 6 m (20 ft), but that all of the material remained in the shorezone (e.g., see Figure 9-11). In effect, the storm damage did not exceed the beach changes caused by a normal winter season. As the winter of 1987/88 was otherwise a low wave energy winter, the sand was returned to the beach berm by the following summer.

In contrast, the 1939 storm appears to have moved sand well offshore from the shorezone and for long distances along the shelf (Figure 9-4). Permanent changes resulted in the crosshore sand budget (see Sections 9.6 through 9.8). It is likely that the deepening off Mission Bay and the shoaling off Point La Jolla shown in comparisons of the 1934 and 1970 surveys (Figure 9-5) also were caused by a northerly transport of sediment associated with the 1939 storm.

El Niño-Southern Oscillation (ENSO)

ENSO phenomena have been discussed in Chapters 4 and 8. El Niño events persist 2 to 7 years and have the strongest coherence for recurrence with periods of 2.8 and 3.5 years (Julian & Chervin, 1978). ENSO events appear to account for most of the wet years during the most recent 30 year period of mild, dry climate (mid-1940's to mid-1970's) along the southern California coast (e.g., winters of 1951/52, 1957/58, 1965/66, 1968/69, 1972/73). In addition, the long periods of drought appear to be terminated by unusually strong El Niño epochs, as in 1939/40, 1940/41, and again in 1979/80 and 1982/83.

Water levels are anomalously higher during El Niño years. Beyond the increase in the number of storms and their associated storm surges due to wind and decreased atmospheric pressure, there is also a large-scale sealevel increase associated with (a) the relaxation of the westward flowing trade winds which causes water to "pile-up" along the west coast of the Americas, and (b) the expansion of the warm surface water with increasing El Niño temperatures. As indicated in Section 4.2.2, the maximum water elevation measured at Scripps Pier in La Jolla between 1925 and 1986 was 2.38 m (7.81 ft) above MLLW in August 1983. The combined effects of storm surges and waves and El Niño events increased water levels approximately 30 cm (1 ft) at tide gage locations during the extreme El Niño winter of 1982/83, and were responsible for extensive coastal flooding and structural damage.

Global Warming

The warming trend in world surface temperatures that began in the mid-1970's peaked with 1988, the warmest year in a 134 year record (see Kerr, 1990). In 1989, the earth's surface was 0.23°C warmer than during the reference period 1951 to 1980, making 1989 the fifth warmest year on record. The decade of the 1980's contained six of the ten warmest years on record. Climatologists suspect, but without unanimous agreement, that the accumulation of greenhouse gases has caused this warming trend during the past 15 years.

If global warming is intensifying, the implications for coastal regions are increased rates of sealevel rise and possibly increased incidence of storm activity (see discussion of ocean surface warming and propagation of tropical cyclones in the Southern California Bight, Section 8.4). Sealevel rise has averaged approximately 20 cm/century (0.7 ft/century) in the San Diego Region (Barnett, 1984; CCSTWS 88-6). Estimates of future rates of sealevel rise vary widely due to the many uncertainties associated with global warming. The Marine Board (1987) has recommended that a rate of 1.3 ft/century be used for 25 year design projects.

Earthquakes and Tsunamis

The northwest/southeast trending coast from Point La Jolla north to Palos Verdes is paralleled offshore by a number of faults. In increasing distance from shore, these faults are the Rose Canyon-Inglewood fault zone, Palos Verdes-Coronado Bank fault zone, San Diego Trough fault zone, and the San Clemente-San Isidro fault zone. All are right lateral faults, with the offshore segment moving north. Although all have been active during the past 10,000 years, none are known to have generated tsunamis during historic times. However, their orientation suggests that the Point La Jolla headland block on the offshore side of the Rose Canyon fault and the San Clemente Island block on the San Clemente fault are potentially intense wave makers for sending tsunamis in a northeast direction against the shoreline of the entire Oceanside Littoral Cell.

The Loma Prieta earthquake of 17 October 1989 demonstrated the potential for upthrust motion associated with bends in the fault line (Anderson, 1990). The earthquake caused initial fears of a tsunami when water was observed rushing out of the Santa Cruz Small Craft Harbor and at Moss Landing. The cause was later determined to be an upward thrust of the Pacific Plate of 4.3 ft above the hypocenter, and an uplift of 0.5 ft at the shoreline (Flavell, 1990).

A recent example of slippage along submarine right lateral faults occurred off the southern coast of Mexico (Fox, 1990). A tsunami generated by the offshore seismic activity swept away 300 homes in the fishing village of Cuajinicuilapa. The powerful but slow-moving tsunami allowed the 1500 residents to evacuate.

Seismic activity has been implicated in sea cliff failure. Kuhn & Shepard (1984) attribute a slump at Sunset Cliffs (Ocean Beach) to the Borrego Valley earthquake of 1968.

Whether from inland or offshore faults, seismic activity can affect the coastal zone of the San Diego Region. The frequency of occurrence of earthquakes and tsunamis is low, but the potential for coastal damage particularly in the Oceanside Littoral Cell is high.

Subsidence

Two leveling surveys at benchmarks along the northern and eastern margins of San Diego Bay reveal an apparent subsidence of about 0.008 ft/year (Moffatt & Nichol, 1989: CCSTWS 88-6). In the vicinity of Lindbergh Field, the artificial fill appears to be subsiding at a rate of 0.02 ft/year. Continued downwarping associated with strike-slip movement across the Rose Canyon fault zone (Kennedy & Welday, 1980) may explain these observations of local subsidence. Along the exposed coast of the San Diego Region, long-term tectonic uplift averaged over the last 125,000 years appears to be occurring at a rate of about 10 cm/millennium (see Inman, 1983).

Assuming there will be local fluctuations in uplift and subsidence associated with the numerous fault blocks in the San Diego Region, the general picture is one of gradual uplift and right lateral slippage between fault blocks. However, this will have relatively little effect on the coast in the short-term unless there is a major earthquake. In areas of local subsidence such as San Diego Bay, sealevel rise will still be more important, but subsidence has the potential of increasing coastal flooding.

9.4 REVIEW OF HISTORIC BEACH PROFILES AND SHELF TRANSPORT

The shorezone is the sedimentary and solid surface associated directly with the interaction of waves and wave-induced currents and the sediments derived from the land. It includes the beach and the shorerise, the gentle steepening of slope leading up to the beach. Along the San Diego Region, the shorezone sands constitute a thin veneer of sediment that extends from the base of the sea cliff seaward over the wave-cut terrace to depths of 10 to 15 m (33 to 50 ft). A generalized diagram of the shorezone sediment thickness in the San Diego Region is shown in Figure 9-9.

9.4.1 Beach Profiles

Recent studies indicate that beaches undergo two types of on-offshore response to wave forcing: a seasonally reversible equilibrium response where the crosshore transports are totally contained within the shorezone; and disequilibrium responses that result in net gains or losses of sediment to the shorezone.

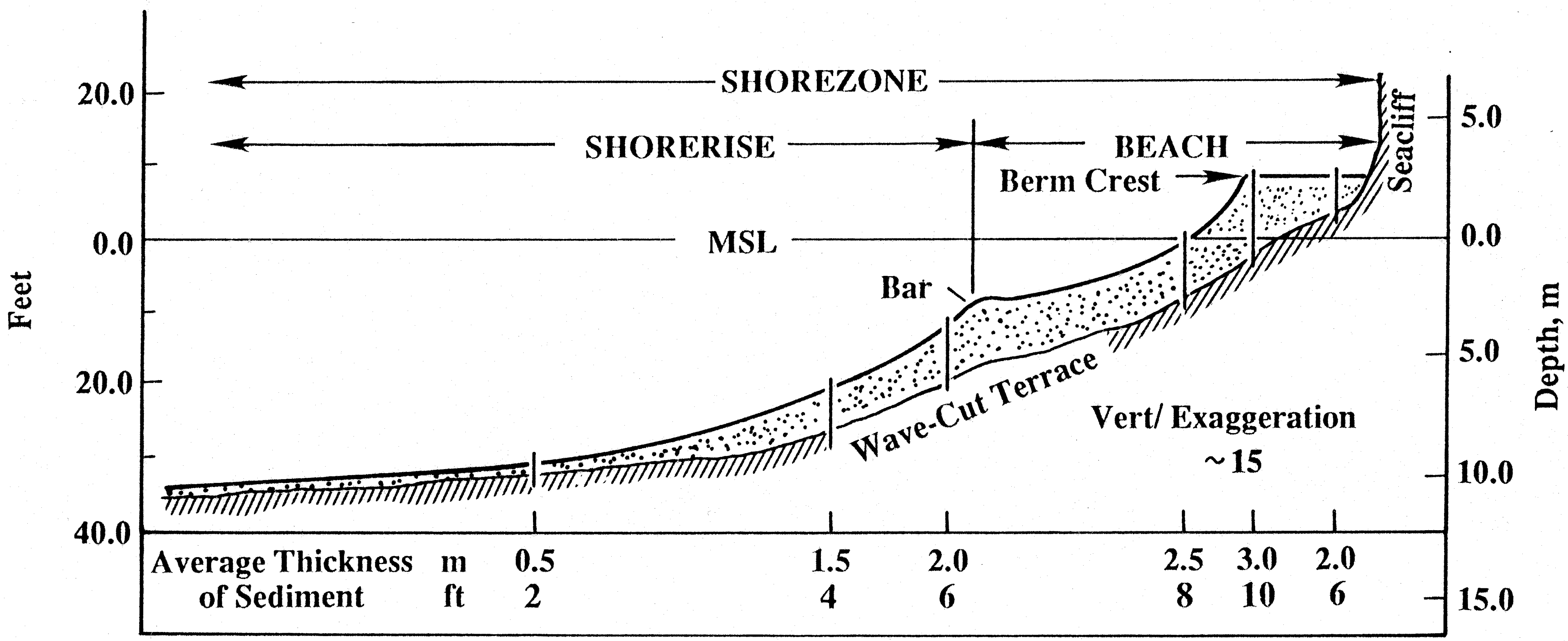

Figure 9-9. Generalized diagram of shorezone sediment thickness over the wave-cut terrace in the San Diego Region. Based on jet probes along typical profiles such as PN1280, PN1240, SD670, SD600, SS50, SS15 (data from CCSTWS 88-5).

Disequilibrium is associated with high-energy storm events and with the steepness of the slope of the shelf seaward of the shorerise. Episodic high total-energy wave events cause sediment to be downwelled and carried seaward of the shorerise. When the slope is too steep, the downwelled sediment is permanently lost to the shorezone. When the slope is not too steep, some sediment may eventually be returned to the shorezone. When the slope is gentle and covered with sediment, normal wave action following the downwelling induces a net onshore transport of sediment into the shorezone again (Inman & Dolan, 1989, p. 209-210). Net onshore transport from the shelf probably occurs from time to time along the Mission Bay and Silver Strand Littoral Cells but to a lesser extent or not at all along the Oceanside cell due to the greater steepness of the shelf in this region.

Seasonal Equilibrium Responses

Seasonal beach profile changes are a classical condition in which seasonal responses to summer and winter waves retain an equilibrium relation to wave forcing. For this case, all material remains in the shorezone and participates in a simple seasonal on-offshore migration in response to summer and winter waves. The winter storms remove material from the beach (bar-berm) portion of the profile and deposit it on the shorerise, where it remains available for transport back to the beach by the smaller waves of summer. Studies at Torrey Pines Beach show that the volume of sand associated with this crosshore seasonal migration ranges from about 60 to 130 m^3 per meter length of beach (72 to 156 yd^3/yd) (Nordstrom & Inman, 1975).

Disequilibrium Responses

High-energy wave events episodically overwhelm the equilibrium conditions of the beach profiles and may cause downwelling of shorezone sand to distances and depths where normal summer wave action cannot return it to the beach. Such events constitute net losses of sand from the shorezone to the shelf. The conditions for such a net change depend upon the intensity and duration (total-energy) of the storm event and upon the slope of the shelf below the toe of the shorerise. A significant increase in slope occurs along the Oceanside Cell at depths of about 18 m (10 fathoms) (Table 9-2). Once material is downwelled to this depth, it appears to be lost from the Oceanside shorezone. In contrast, the shelf slopes at depths of 18 m (10 fathoms) are quite gentle off Mission Bay and Silver Strand, and downwelled material may be available for return to the shorezone.

Profile Analysis

Historical profiles in the San Diego region show reasonable consistency when the outer portion (shorerise) is separated from the inner portion (bar-berm) at the breakpoint (Chapter 5, Inman, et al., 1993). Both portions have curves of the form

$$h = Ax^m$$

where, for simplicity of expression, x is positive offshore, h is positive downward, and the two curves have different origins; that for the bar-berm is near the berm crest whereas that for the shorerise is near the bar with h measured from MSL (Inman, et al., 1993). It is found that both the shorerise and the bar-berm curves have values of m of about 0.4. The principal difference between seasonal profiles is that in winter the breakpoint (bar) is deeper and farther offshore while the berm crest is displaced landward. This results in an increase in the distance between the origins of the bar-berm and shorerise curves, producing an overall decrease in the winter beach slope from the berm crest to the depth of closure of the profile.

The net onshore stress exerted by ocean waves on bottom sediments decreases with increasing depth. Therefore the slope of the equilibrium profile of the beach also decreases with depth, as shown in Figures 9-9, 9-10, and 9-11. At depths of 5 and 10 m (16 and 33 ft), waves can effectively move sand upslope when the slopes do not exceed 4% and 2%, respectively. However, when slopes exceed about 1% in depths of 20 m (65 ft), waves cannot return the sediment to the beach. Since the shelf slopes off the Oceanside cell are generally steeper than 1% in depths of 20 m (65 ft) (see Table 9-2 and Figure 9-15), sand transported seaward of the shorerise does not return to the beach. In contrast, Silver Strand Littoral Cell has the steepest slopes in the shorezone, but the most gentle beyond that depth (0.4% from 20 to 50 m) . Therefore sand can be returned to the beach from greater depth in that cell. In depths of 20 to 50 m (66 to 164 ft), the Mission Bay shelf is intermediate in slope (1.1%) between Oceanside (1.3-2.0%) and Silver Strand (0.4%).

The data show that the initial response to unusually high waves and storms is a landward recession of the berm and a seaward and deeper location of the breakpoint bar (Figure 9-11). A single storm may have relatively little efffect on the outer portion of the shorerise. However, years with a series of intense storms (storm clusters) may show severe erosion of the shorerise and bar-berm profiles. Erosion of the toe of the shorerise (i.e., deepening of 1.2 m = 4 ft and more) in depths of 12 to 15 m (40 to 50 ft) occurred along the open coast following the winters of 1952/53, 1979/80 and 1982/83 (e.g., Figure 9-10). These were years during which storm clusters battered the southern California coast (Chapters 4 and 8). Interestingly, the most intense storm of the century (January 1988) had little effect on the deeper portions of the shorerise profile, probably because the storm was of short duration and was the only storm of significance during that otherwise mild winter (Figures 9-10 and 9-11). It is known that

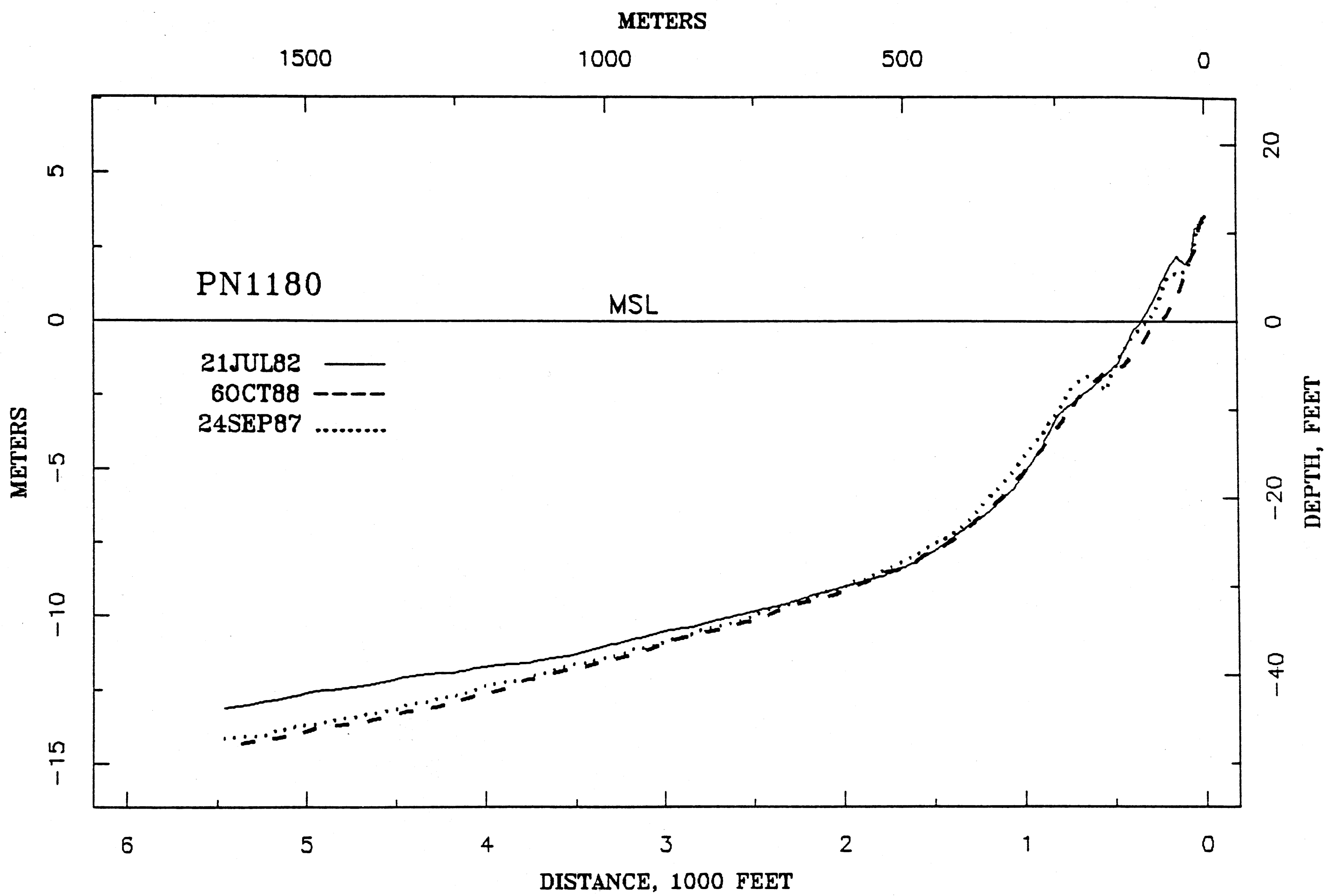

Figure 9-10. Deepening at the toe of the shorerise associated with the cluster storms of 1982/83 for a range north of Oceanside.

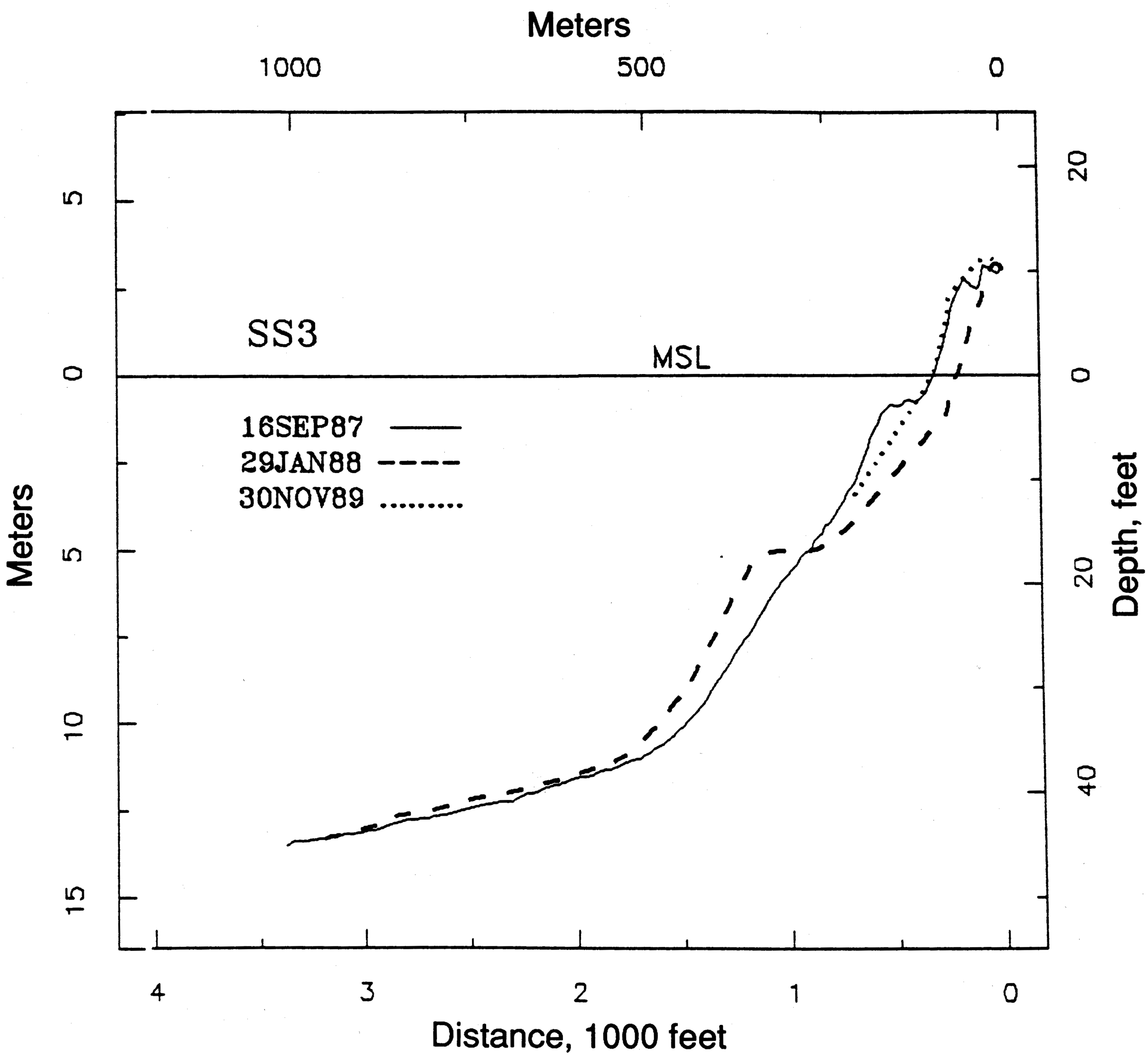

Figure 9-11. Effect of the January 1988 storm (dashed line) on the bar-berm profile at Silver Strand Beach.

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the tropical storm of 1939 caused major damage to beaches. However, there are no beach profiles available from the decade following that storm, even though four profiles go back in time to 1934 (Table 9-9).

The historic data show that significant erosion of the entire profile (shorerise and bar-berm) occurs sporadically in time and only following storms of high total-energy or storm clusters. Further, the erosion is greatest when the storms make their landfalls locally, subjecting the nearshore waters to the full spectrum of wave frequency and direction. The most severe erosion in the record of historical profiles was caused by the cluster storms of 1982/83 (Figure 9-10, Table 9-10). Although the bar-berm portion of the beaches gradually recovered over a period of about five years, the erosion at the 12 m (40 ft) depth still remains apparent along many profiles (Figure 9-10).

Closure Depth

The sand participating in seasonal beach changes remains within the shorezone. The maximum depth of seasonal changes is about 10 m (33 ft) and is referred to as the "closure depth" (Figure 9-9; Chapter 5). The closure depth is best illustrated from a plot of depth versus the standard deviation of depth changes from repeated surveys of the same profile as shown in Figure 9-12. It is apparent that profile changes at depths greater than about 6 m (20 ft) MSL were insignificant for Range PN1240 during the period of January 1984 to December 1989. However, downwelling of sediment below the shorerise occurred during the cluster storms of 1982/83 (Figure 9-10) and periodically before that time. Therefore a similar plot for that range over the preceding period from 1950 through 1983 (Figure 9-13) shows a secondary increase in standard deviation below depths of 10 m (33 ft) MSL, and hence a lack of closure. It is interesting that the bimodality in the standard deviation of depth change occurs to either side of a depth of about 10 m (33 ft) MSL, which coincides with the closure depth at the toe of the shorerise (Figures 9-10 and 9-11).

In summary, the beach profile response is very different for storm cluster episodes than for years with a more uniform, milder wave climate. During mild years there are seasonal beach changes that may extend to, but do not exceed, the closure depth of about 10 m (33 ft). When the seasonal cycles are averaged over the year, it is found that little or no net erosion results (Inman, 1956; Nordstrom & Inman, 1975; Winant, et al., 1975; Aubrey, et al., 1980). However, the erosion that occurs during storm cluster episodes extends to depths in excess of 15 m (50 ft), and there is no closure out to the greatest depths profiled. These storms appear to be the cause of significant long-term, irreversible erosion. In the vicinity of Camp Pendleton and Oceanside, the deeper portions of the shorerise profile have not recovered from

TABLE 9-9
HISTORICAL BEACH PROFILES
SAN DIEGO REGION

Littoral Cell	Range[a]	Date of Initial Survey 30 ft	40 ft	# Surveys to 30 ft	40 ft
Oceanside	SC1720	1965	--	7	0
	SC1660	1968	1986	6	4
	PN1280	1972	1972	7	0
	PN1240	1950	1972	10	6
	PN1180	1972	1972	7	7
near	PN1110	1950	1972	7	14
harbor	OS1070	1959	1964		18
	OS1030	1959	1964	24	14
	OS1000	1961	1962	19	13
	OS930	1972	1972	7	7
	OS900	1961	1964	15	12
	CB800	1970	1970	8	8
	CB720	1934	1934	9	9
	SD670	1934	1934	6	6
	SD630	1934	1934	7	6
	TP540	1934	1934	6	5
Mission Bay	MB384	1972	1986	5	4
	MB340	1940	1949	10	8
	MB310	1940	--	10	0
	OB230	1951	1951	13	7
Silver Strand	SS50	1954	1956	17	8
	SS15	1965	1975	7	0
	SS3	1969	1986	6	5

[a] Range numbers increase from south to north. Letters designate: SC, San Clemente; PN, Camp Pendleton; OS, Oceanside; CB, Carlsbad; SD, San Diego County; TP, Torrey Pines; MB, Mission Beach, OB, Ocean Beach; SS, Silver Strand.

Source: CCSTWS Appendix B

TABLE 9-10
VOLUME CHANGES ALONG BEACH PROFILES MEASURED TO DEPTH OF 10 M (33 FT)
COMPARED WITH THOSE TO 13 M (43 FT) IN THE VICINITY OF OCEANSIDE[a]

	Distance from[b] Oceanside Harbor		Measured to 10 m (33 ft) MSL				Measured to 13 m (43 ft)MSL			
			82/83 Change[c]		86/89 Ave[d] Change vs 72		82/83 Change[c]		86/89 Ave[d] Change vs 72	
Range	km	(10^3 ft)	m^3/m	(yd^3/yd)	m^3/m	(yd^3/yd)	m^3/m	(yd^3/yd)	m^3/m	(yd^3/yd)
PN1280	6.7N	(22)	-380	(-460)	+20	(+24)	-1050	(-1200)	+60	(+75)
PN1240	5.5N	(18)	-15	(-18)	+30	(+40)	-900	(-1080)	-120	(-150)
PN1180	3.7N	(12)	-100	(-120)	-230	(-270)	-630	(-750)	-750	(-900)
PN1110	1.5N	(5)	+1150	(+1380)	+1530	(+1830)	+1500	(+1800)	+1630	(+1950)
OS1070	1.0S	(3)	+190	(+230)	-740	(-880)	+280	(+330)	+230	(+270)
OS1030	2.1S	(7)	+380	(+460)	-230	(-270)	+380	(+460)	-230	(-270)
OS1000	3.0S	(10)	-240	(-290)	-40	(-50)	-480	(-570)	-630	(-750)
OS900	5.8S	(19)	+75	(+90)	+190	(+230)	-180	(-210)	0	(0)

[a] Data from CCSTWS Chapter 3 Appendix, selected for surveys extending to 13 m depth.

[b] Distance north (N) and south (S) of centerline of Oceanside Harbor.

[c] Comparison of surveys of summer 1982 with summer 1983, or next available.

[d] 1972 is the common reference year before 1982/83 cluster storms.

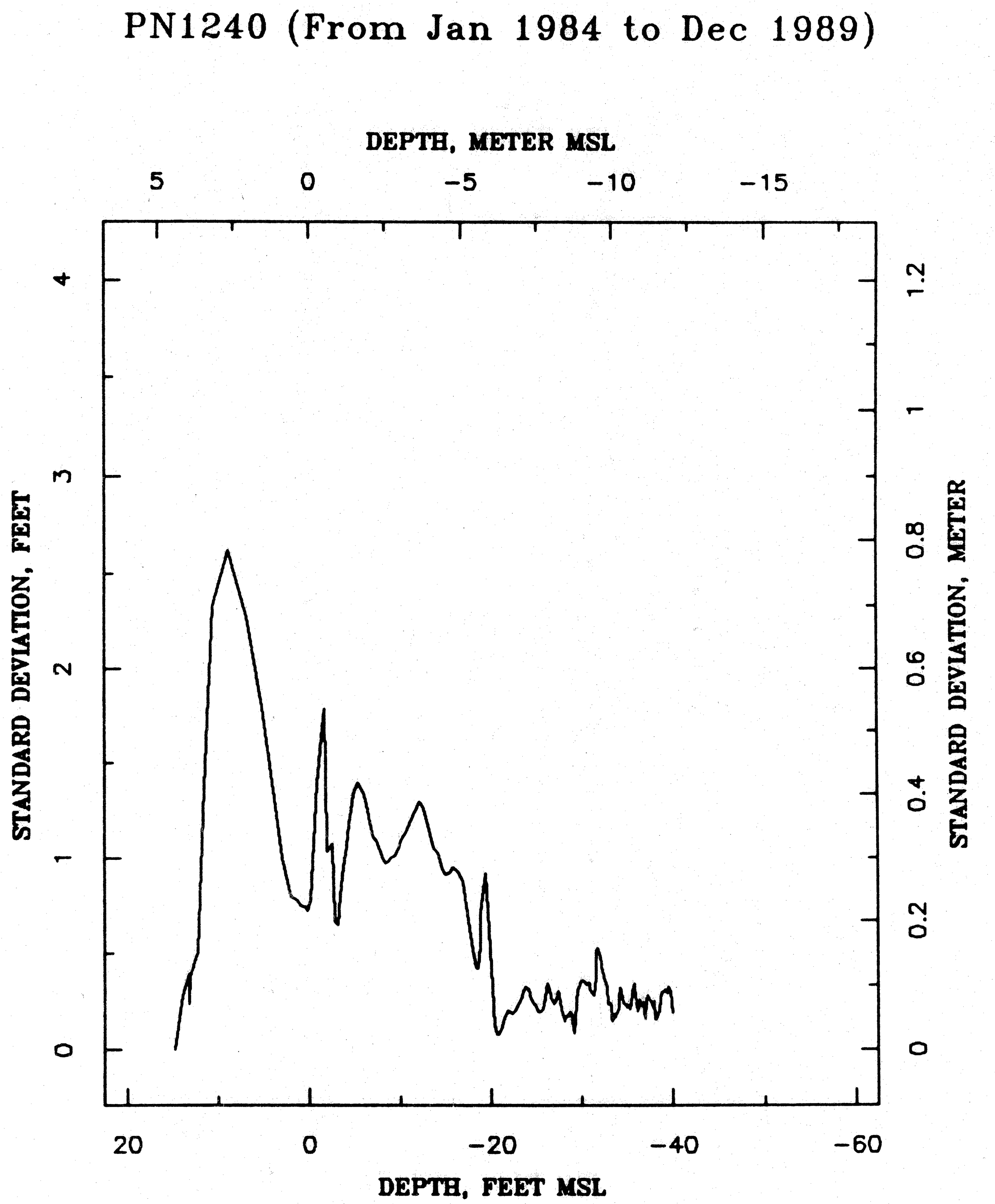

Figure 9-12. Depth of closure for the period January 1984 to December 1989 on range PN1240. Depth of closure is about 6 m (20 ft) MSL as shown by the reduction in standard deviation of the depth changes to about 10 cm (0.3 ft) (from Inman, et al., in press).

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PN1240 (From 1950 to end of 1983)

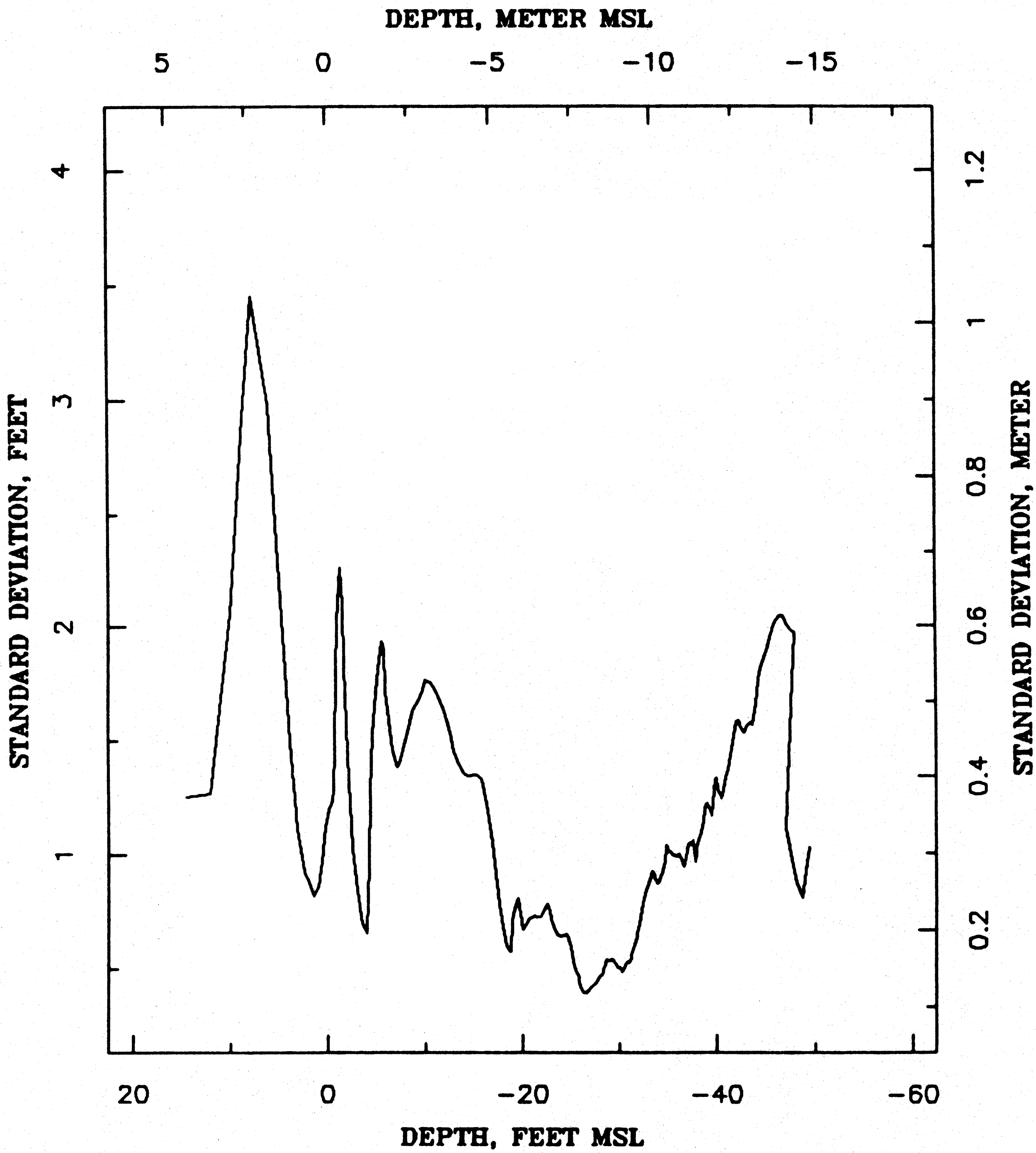

Figure 9-13. Bimodal distribution of standard deviation of depth change indicating a lack of closure for this period. Compare with Figure 9-12 and Chapter 7 (Figure 7-22).

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the 1982/83 storm cluster episode (Figure 9-10). In contrast, the most severe storm of the century (January 1988) acted as though it was a typical, albeit severe, winter storm, with profile changes restricted to the closure depth for seasonal changes. The beaches fully recovered during the following summer season (Figure 9-11).

The coastal reach most affected by a particular storm is critically dependent on the degree of island sheltering associated with the direction of approach of the storm waves. For example, the 1979/80 and 1982/83 storm clusters approached from west to west-southwest and were most damaging in the vicinity of Oceanside and Silver Strand. Santa Catalina Island partially sheltered the San Clemente section of coast, while San Clemente Island partially sheltered the coast from Del Mar to Point Loma. The 1939 tropical storm, on the other hand, approached from the south and inflicted damage on the coast from the Mexican border to Dana Point. The storm cluster of 1955/56, with storm paths approaching from the west-northwest, damaged the coastal section from Del Mar to Point Loma. As might be anticipated from the foregoing analysis, the shorerise profiles in this region underwent permanent erosion during these storm events (DLI photo collection; profiles CB720 and MB340).

A question of accuracy and reliability of data naturally arises in comparing the historical beach profiles and interpreting their depth changes. The depth changes exceed the presumed accuracy of fathometer surveys, which for carefully controlled profiling was shown by Inman & Rusnak (1956) to be about ± 1 ft in elevation and ± 15 ft in position. In addition, there is spatial consistency in the depth changes along the coast which resulted from the 1982/83 storm cluster events. Errors in bench mark relocation or elevation cannot explain the 1.2 m (4 ft) changes along the gentle slopes (0.6%) at depths of 12 m (40 ft) and greater (Figure 9-10), nor the fact that the changes occur only in the lower portions of the profiles. Finally, the CCSTWS historical profiles are in agreement with the shoaling and deepening trends detected in the NOAA surveys of 1934 and 1970 (e.g., Figure 9-15).

9.4.2 Oceanside Harbor and the 10-Fathom Sink

The orientation of the northern breakwater at Oceanside Harbor induces strong, artificial rip currents that intercept longshore transport and shunt the sand offshore into deeper water (Figure 9-14). The sand is deposited in the notch caused by the 10-fathom terrace cut during lower sealevel about 9 to 10 thousand years ago, as shown by the profiles in Figure 9-15. The terrace slopes are locally steeper than the equilibrium profile of the beach, preventing the onshore transport of sand by subsequent wave action. Waves and currents acting over the steepened profile induce a contour-parallel transport. The presence of this accretion band

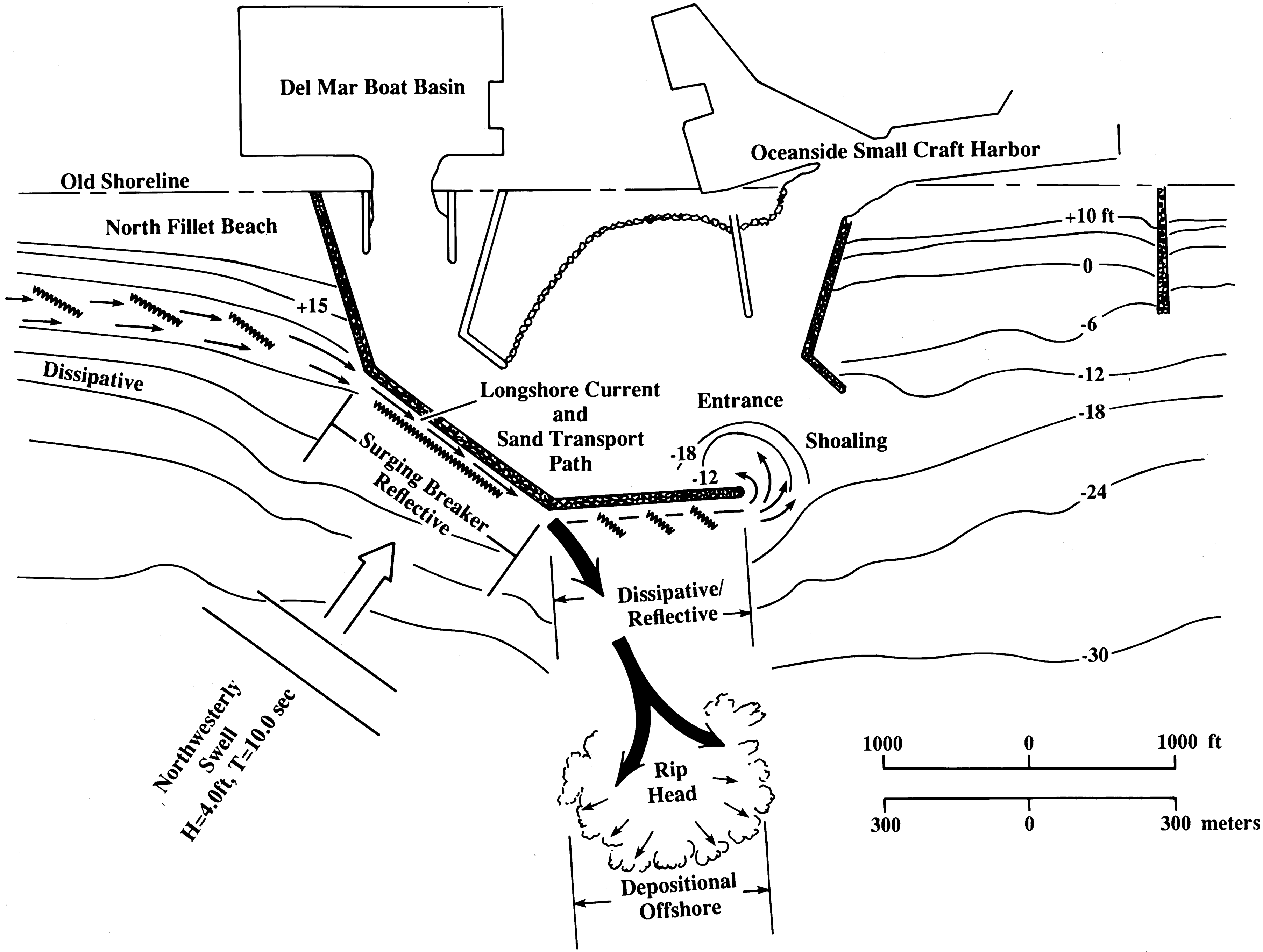

Figure 9-14. Formation of a surging breaker zone and strong rip current that transports sediment offshore at Oceanside Harbor (from Inman & Jenkins, 1983; 1985).

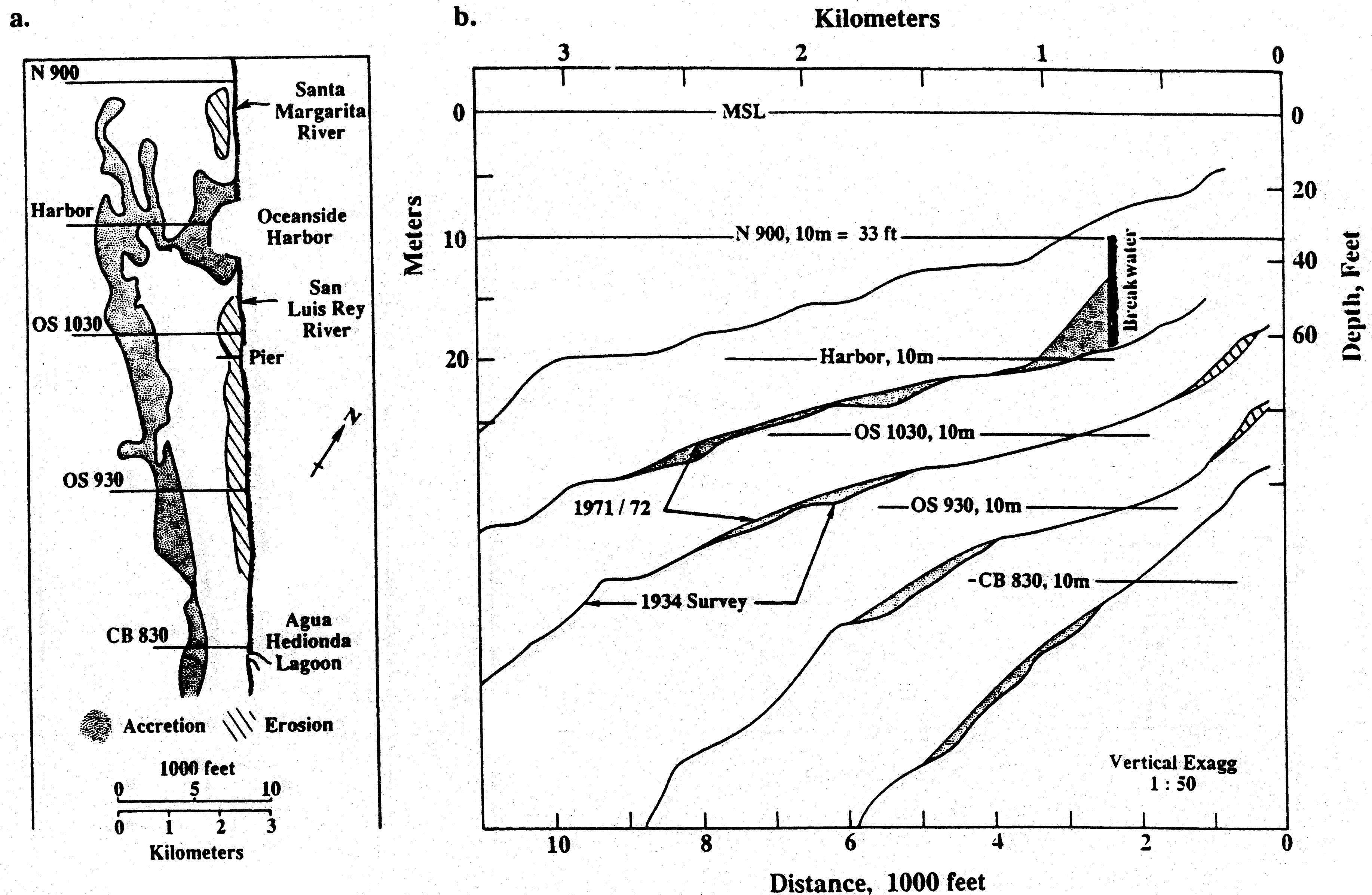

Figure 9-15. Deposition of sediment along the 10-fathom notch in vicinity of Oceanside Harbor based on comparison of NOAA hydrographic surveys of 1934 and 1970/71. (a) Plan of accretion and erosion (after Dolan, et al., 1987). (b) Profiles showing thickness of accretion and erosion. (from Inman & Masters, n.d.).

was noted by Dolan, et al. (1987), who calculated a volume of 3.4 million cubic meters (4.4 x 10^6 yd^3) for the 12 km (7.5 mi) section of coast extending from north of Oceanside Harbor to Agua Hedionda Lagoon (Figure 9-15a).

Using the profiles in Figure 9-15, the volume of accretion along the 10-fathom terrace is estimated to be 5.6 million m^3 (7.3 x 10^6 yd^3). An additional 1.3 million m^3 (1.7 x 10^6 yd^3) of sand has accreted around the harbor. During the 14 year period between the extension of the north breakwater in 1958 and the 1971/72 surveys, therefore, a total of roughly 7 million m^3 (9 x 10^6 yd^3) of sand may have been diverted from the littoral transport path. This volume corresponds to the 7 million m^3 of erosion along Oceanside's downcoast beaches between 1958 and 1972 computed by Inman & Jenkins (1983).

Inspection of Figure 9-4 and Table 9-5 shows that deposition of material along the 10-fathom notch is far more extensive along the Oceanside cell than that shown locally in Figure 9-15a. This observation raises the question of the importance of local seaward deflection of sediment by the harbor relative to more general downwelling events along the coast. That is, what percentage of the deposition shown in Figure 9-15 is related to the harbor and what percentage is the result of natural downwelling? Analyses by Dolan, et al. (1987: CCSTWS 87-4) indicate that the harbor is a major contributor whereas Everts (1990: CCSTWS 90-2) attributed the phenomenon to natural downwelling processes. Resolution of this problem is essential to understanding the beaches downcoast of the harbor. The budget analysis in Section 9.6 suggests that the facts lie somewhere between the two extremes.

9.4.3 Comparison of Profile Change, Shelf Accretion and Erosion of Blufflands

A review of the beach profiles in the San Diego Region yielded 23 that extend back to 1972 or earlier; these are designated as "historical" profiles. Of these, 19 have four or more surveys that extend to depths of 13 m (43 ft) below MSL: 14 in the Oceanside, 3 in the Mission Bay, and 2 in the Silver Strand Littoral Cells (Table 9-9).

Eight ranges in the Oceanside cell extending to depths of 13 m (43 ft) MSL were found to bracket critical events such as the May 1981 beach nourishment program at Oceanside and the cluster storms of 1982/83 (Table 9-10). Two are within 1.5 km (1 mi) of the center of Oceanside Harbor; three are 3.7 to 6.7 km (2 to 4 mi) north of the harbor and represent undisturbed open coast effects; and three are 2.1 to 5.8 km (1.5 to 3.5 mi) south of the harbor and show the effects of sand trapping by the harbor, as well as beach nourishment.

Total volume changes can differ significantly between profiles when they are summed to depths of 13 m (43 ft), in contrast to depths of 10 m (33 ft) MSL. Table 9-10 shows that the additional 3 m (10 ft) depth magnifies the volume change by a factor of five along the three northern profiles. For example, the average change for the cluster storm year of 1982/83 is -165 m^3/m when computed to a depth of 10 m, and -860 m^3/m when computed to a depth of 13 m. These storms produced deepening of 1.2 m (4 ft) at depths between 10 m and 13 m (33 and 43 ft). As shown in Figure 9-10, the depth increase occurred after the survey of June 1982 and persisted through the last deep survey of September 1987. Inspection of the profiles shows that the deepening continues beyond the seaward limit of the profiles, indicating that the total volume change is probably much larger than that calculated to the 13 m (43 ft) depth.

The average profile change of -860 m^3/m for 1982/83 cluster storms can be compared with the yield of coarse sediment from coastal blufflands erosion of 12 m^3/m-yr (Table 9-6) and the accretion rate on the shelf off Camp Pendleton of 13 m^3/m-yr (Table 9-5). The bluff erosion rate and the shelf accretion rate nearly balance. But the profile changes during cluster storm years are equivalent to about 70 years of "normal" bluff erosion and shelf deposition.

It is of interest to note that the historic shelf deposition rate between depths of 0 and 37 m (0-120 ft) (Table 9-5) and the yield from the coastal blufflands (Table 9-6) are both an order of magnitude greater than the rate of deposition on the continental shelf during the Holocene (Table 9-4). This difference may be due to the fact that the narrow shelf off Oceanside is basically a wave-cut phenomenon with most deposition occurring in depressions related to notches from former seacliffs, stream valleys cut across the shelf, and faults on the shelf. Other than these deposits, material found on the shelf is probably in transit, either longshore to submarine canyons or offshore beyond the shelf break. Note that the Oceanside shelf steepens to about 2% in the depth range of 50 to 80 m (165 to 265 ft). Also, compaction will eventually reduce the fine sediments to only a fraction of their original volume.

9.5 MODEL FOR THE BUDGET OF SEDIMENT

A shoreline model based on the continuity relations following Inman & Dolan (1989) is described in this Section and applied in Sections 9.6 through 9.8 to coastal processes within the three littoral cells of the San Diego Region. In Chapter 7, an iterated (time-stepped) model was employed to derive detailed shoreline changes along small control cells. In this Section, the integrated model will provide an overview of littoral sediment budgets for subcells defined by natural or artificial boundaries within the three main cells of the San Diego Region. Their budgets of sediment and associated shoreline changes provide a test of our understanding of processes and their quantitative effects on the coast.

The integrated form of the continuity relation for the volume-flux of sediment in a control cell is

$$\partial V/\partial t = \Sigma Q_x + \Sigma Q_y \qquad (9\text{-}1)$$

where $\partial V/\partial t$ is the volume change in a cell of length ℓ and Q_x and Q_y are the onshore and longshore components of volume fluxes into (+) and out of (-) the cell (Figure 9-16).

It follows from equation (9-1) that there will be a change in the volume of sediment in the control cell when the summation of the budget does not equal zero ($\partial V/\partial t \neq 0$). Beaches along sandy coasts attain energy profiles that are in equilibrium with the waves that form them. For the prevailing wave conditions, any change in the shape of the profile will result in a change in the position of the shoreline. The shoreline position then varies with time and season. Averaged over a longer period such as a number of years, the seasonal profile changes result in no net gain or loss of sand to the beach. The shoreline movement $\partial X/\partial t$ is included in the continuity model by introducing a flux-surface at the shoreline that moves to compensate for the net gain or loss of volume resulting from the divergence of the volume transports through the cell. The shoreline flux-surface will have longshore length ℓ and vertical height Z equal to that defined for the fixed-form translational profile that is assumed to move a horizontal distance equal to the shoreline change. Using the sign convention illustrated in Figure 9-16 and Table 9-11, the volume-flux Q_f through this flux-surface that results in shoreline change $\partial X/\partial t$ will be given by

$$\partial X/\partial t \cdot Z \cdot \ell \equiv Q_f \qquad (9\text{-}2)$$

where $Z \equiv q'$ is the volume-equivalent factor (m^3/m^2) defined in Chapter 5 (equation 5-2). For a translational type, fixed-form profile, Z is identically equal to the vertical height of the flux-surface (i.e., the "closure height") and $Z = h_c + c$ where h_c is the closure depth and c is the berm height above MSL.

Note that the direction in which the sediment mass moves relative to the moving flux-surface determines the sign of Q_f. Q_f is positive for shoreline erosion ($\partial X/\partial t$ positive) and negative for shoreline accretion ($\partial X/\partial t$ negative), in agreement with equation (9-2) and Figure 9-16. Q_f is one of the x-components of the budget; its sign (subscript $_1$ or $_2$ in Figure 9-16) depends upon the sign of $\partial X/\partial t$. When all factors relating to volume change in the control cell are summed, except Q_f, then

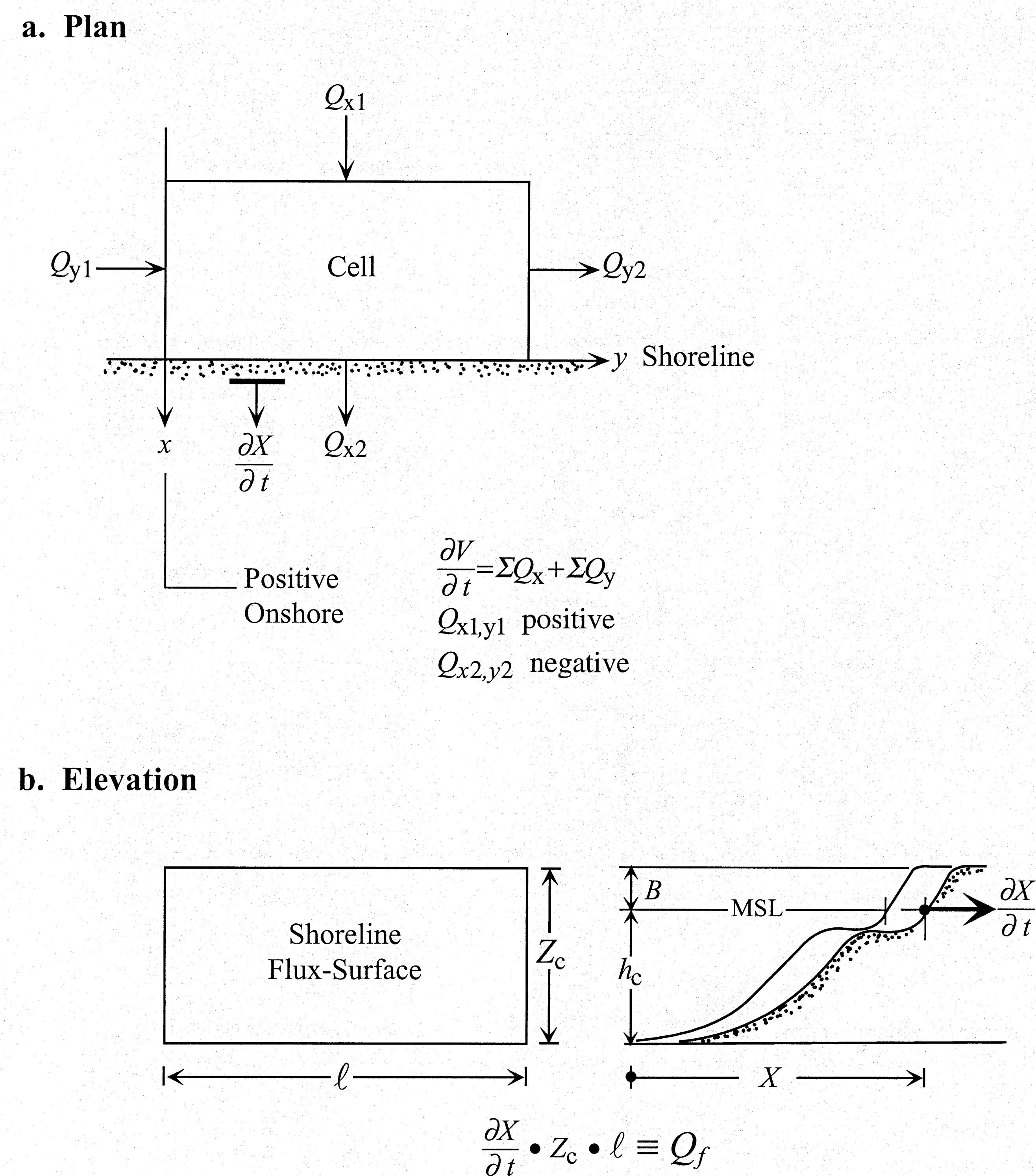

Figure 9-16. (a) Control cell for the balance of sediment volume with (b) flux-surface with height Z moving at velocity ∂X/∂t at the shoreline to account for erosion (+) and accretion (-) (after Inman & Dolan, 1989).

Table 9-11
BUDGET SYMBOLS

Variables

q = volume transport rate of sandy material, m^3/m-yr (yd^3/yd-yr)

Z = q' = height of the shoreline flux-surface (m) and volume-equivalent factor for shoreline change, m^3/m (yd^3/yd)

Q = $q' \cdot \ell$ = total sand transport rate into or out of cell, m^3/yr (yd^3/yr)

ℓ = length of control cell

General Subscripts

1 = flux into cell (+)

2 = flux out of cell (-)

a = artificial nourishment, bypassing, dredging, etc. (+/-)

b = blufflands erosion (+); includes sea cliff, gullies, coastal terrace, slumps, etc. as distinct from rivers

f = shoreline flux-volume into control cell (+) by shoreline erosion, or deposition of material out of cell (-) by shoreline accretion, in accordance with movement of shoreline flux-surface, $\partial X/\partial t \cdot Z \cdot \ell = Q_f$

I = inlet material, i.e., carried in or out by inlet flow (+/-)

ℓ = longshore transport of sand in and near the surfzone, versus *n*

n = nearshore transport along the coast, outside the surfzone

o = on/offshore transport at the base of the shorerise (+/-)

ow = overwash (-)

r = river yield to the coast (+)

s = lost into submarine canyons (-)

w = windblown sand (-)

Harbor Effects Subscripts

ab = artificial bypassing (+)

at = bypass material retrapped (-)

ℓd = longshore deflected to deep water (-)

ℓt = longshore trapped in harbor (-)

nd = nearshore deflected to deep water (-)

$$\partial V/\partial t = \partial V'/\partial t + Q_f$$

where $\partial V'/\partial t$ is the volume sum neglecting the effects of shoreline change. For the condition of a balanced budget of sediment $\partial V/\partial t = 0$, and

$$Q_f \equiv - \partial V'/\partial t \qquad (9\text{-}3)$$

Review of historical profiles in the preceding section shows that the beaches in the Oceanside Littoral Cell are markedly reduced in volume during the episodic occurrences of high total-energy storms. Between these events, the beaches gradually recover in total volume. Consequently, there is no meaningful closure height Z (equation 9-2) that pertains to beach changes for these episodic storm periods. We only have meaningful measures of Z for periods of normal seasonal beach changes (compare Figures 9-12 and 9-13). Therefore, it is useful to select time intervals for our model that exclude these episodic events and compare the observed shoreline changes with the model changes obtained from equations 9-2 and 9-3.

The following paragraphs discuss a number of other limitations and special assumptions which must be considered in the application of the model to real shorelines. These include determining meaningful depths of closure, the problems related to changes in sealevel, and evaluation of the longshore transport of sand on the shorerise outside of the surfzone.

Closure Height. The shoreline change model (Figure 9-16; equation 9-2) requires that the beach profile be represented by some mean profile of translation that is highly correlated with the net volume change in the control cell Q_f and the height of the flux-surface Z, here referred to as the closure height. This requirement means that "seasonal" crosshore beach changes must be contained within the shorezone above a constant depth of closure h_c at the toe of the shorerise. The condition of profile closure is the only condition under which the height of the flux-surface Z is identically equal to the volume-equivalent factor q' (refer to the discussion in Section 5.2.2). It is apparent from the study of historical profiles (Section 9.4) that in general, there is no long-term closure depth (Figure 9-13), although there are periods, usually less than a decade, between high total-energy wave events when the depth of closure remains nearly constant (Figure 9-12). Interpretation of the budget is thus strongly dependent upon the presence or absence of these high total-energy events. To cope with these episodic events, it is convenient to balance the budget within time periods dominated by a single type of wave climate.

Sealevel Rise. As the control cell for evaluating the budget of sediment is considered to include the translational beach profile, the redistribution of sediment associated with sealevel rise is assumed to occur entirely within the volume of the "box" that constitutes the control cell (see Inman & Dolan, 1989). Because the amount of the redistribution due to sealevel change is small and the rate is gradual and extends through the times of seasonal changes in beach profile, the redistribution is integrated into the measured profile changes. Consequently, as discussed in Section 5.2.2, the change in shoreline $\triangle x_r$ resulting from sealevel rise $\triangle z$ does not contribute to the volume-flux Q_f into or out of the cell, but must be subtracted from any measured shoreline change which includes adjustments due to sealevel rise and other processes. Another way of viewing this is to consider that the entire box constituting the cell moves onshore a distance $\triangle x_r$ in a Lagrangian frame of reference as discussed in Inman & Dolan (1989, p. 231-232). From Table 5-1, the shoreline recession $\triangle x$ at Torrey Pines Beach is about 9 cm/yr (0.3 ft/yr) assuming a sealevel rise of 0.2 cm/yr (0.0065 ft/yr). Accordingly, the shoreline change $\partial X/\partial t$ applicable to the volume-flux Q_f in equation (9-2) is the measured value minus 9 cm/yr (0.2 ft/yr).

Longshore Sand Transport. Longshore transport of sand is transport within the surfzone, usually assumed to take place over the crosshore distance between the highest breaking wave and the maximum runup on the beach face. This transport has been much studied and relations for predicting it are well known (refer to Section 5.3). This motion is usually thought to be the predominant mode of longshore transport because longshore currents are strong and most energy of the advancing wave is released into surfzone waters. Here, the estimated rate of longshore sand transport in the surfzone is designated by Q_ℓ.

However, sand well outside the surfzone is also moved by waves and currents, but the relative importance of longshore sand transport on the shorerise (Figure 9-9) has not received sufficient study to place it in qualitative or quantitative perspective. The study of historical beach profiles with the abundant evidence of extensive motion to depths in excess of 15 m (50 ft) emphasizes the importance of crosshore transport, and by implication that of longshore transport of sand on the shorerise portions of the shorezone. It is observed that much of the crosshore transport on the shorerise is associated with longshore components of motion due to obliquely approaching waves and coastal currents. Calculations of the longshore component of motion on the shorerise (Inman & Masters, n.d.) suggest that longshore transport of sand along the shorerise is at least 10%, and perhaps 20%, of that in the surfzone. Accordingly, in this study we assume that the longshore sand transport on the shorerise, Q_n, is 10% of the estimated transport in the surfzone, i.e., $Q_n = 0.1\ Q_\ell$.

Interpretation of the Model. Rigorous interpretation of the model requires that all of the driving forces and sediment responses be obtained in a meaningful way, averaged over the same time intervals, and that the variance of the data set is small compared to the mean. Further, it is assumed that the sediment responses to forcing by elements in the regional climate and the incident wave climate are direct and without significant phase lag. In practice, these requirements and assumptions are rarely met.

Many investigators use the sediment budget to solve for an unknown budget contribution such as the longshore transport of sand. This procedure requires that estimates of all other factors be accurate. Such an enforced balance of the budget may overlook important discrepancies which serve as signals for problems in our understanding of the underlying physical processes. The real value of the budget procedure is to enter best estimates of all items and then learn from the discrepancies. In what follows, the best estimates of factors contributing to the budget are entered without constraints except for the shoreline-change flux Q_f which is evaluated separately because of the uncertainty in the value of the closure height Z, as discussed above. Thus the budget is used here as an informative tool and guide.

9.6 OCEANSIDE LITTORAL CELL

The Oceanside Littoral Cell extends for 90 km (56 mi) from Dana Point to Point La Jolla (Figure 9-1). The coast consists of relatively narrow, semi-continuous sandy beaches backed by wave-cut seacliffs. Some of the seacliffs are over 90 m (300 ft) high, as along Torrey Pines State Reserve, and present some of the most spectacular seascapes in the world.

The cell includes two harbors for small craft, Dana Point Harbor and Oceanside Harbor. Dana Point Harbor, located at the northern end of the littoral cell, is essentially free of siltation problems. Oceanside Harbor is in the center of the "river of sand" for the littoral cell, and as a consequence, it is a major trap for littoral sand.

The cell is divided into three subcells based on natural physiographic units: (1) Dana Point to San Mateo Point, (2) San Mateo Point to Carlsbad Submarine Canyon, and (3) Carlsbad Submarine Canyon to Point La Jolla (Figure 9-17). The north subcell is dominated by the lowlands adjacent to San Juan Creek and San Mateo Creek and receives less contribution from bluffland erosion than the southern two subcells. The central and south subcells are separated by the Carlsbad Submarine Canyon, with a wider continental shelf to the north and narrower to the south. The presence of Oceanside Harbor disrupts the budget in complex ways by both impounding material and deflecting material seaward beyond the shorezone. Carlsbad Submarine Canyon is a possible sink for

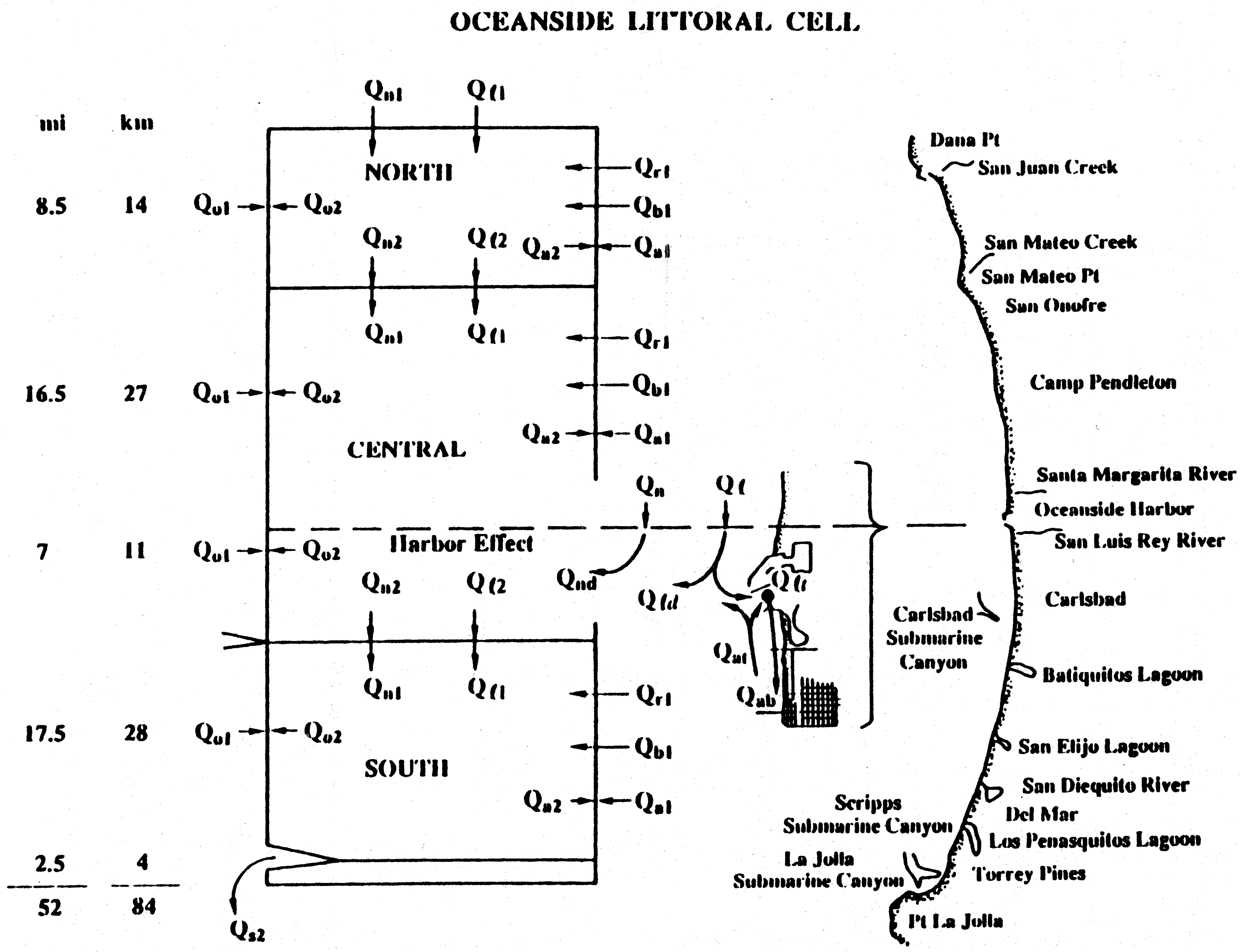

Figure 9-17. Elements of the control cells for the sediment budget for Oceanside Littoral Cell and its three subcells. Harbor effect shown as inset to the central subcell. Symbols are defined in Table 9-11.

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sediments transported along the shelf beyond the shorezone (Figure 9-4). The southern subcell is terminated by Scripps and La Jolla Submarine Canyons, which act as a sink and create a total barrier to further longshore transport southward.

The analysis of the budget of sediment for this cell has been carried out for three time periods: (1) the period from about 1900 to 1938 (Table 9-12), (2) a mild, uniform weather period from 1960 to 1978 (Table 9-13), and (3) a period of more variable wave climate covered by the CCSTWS studies from 1983 to 1990 (Table 9-15). The "natural" budget permits an uncluttered look at the cell as it predates construction of dams and Oceanside Harbor, although it necessarily draws on some findings from later studies. The mild, uniform period from 1960 to 1978 is selected to evaluate the effects of Oceanside Harbor at a time when the wave climate was consistent from year to year and less variable than the present wave climate. The last period of more variable climate (1983-1990) emphasizes the change in wave climate from one that gave a consistent, strong southerly littoral transport to one that gives a more variable transport with a net northerly component in some years.

9.6.1 Analysis of the Budget of Sediment

Several general assumptions are made in arriving at the budget of sediment:

(1) We employ the 10% approximation rule and round off volume estimates from 5,000 to 100,000 to the nearest 5,000 and estimates over 100,000 to the nearest 10,000.

(2) Based on the analyses of Inman & Masters (n.d.), it is assumed that a longshore transport of sand Q_n occurs outside the surfzone in an amount equal to 10% of the surfzone longshore transport Q_ℓ(see Section 9.5).

(3) When other budget quantities balance, sealevel rise of 0.2 cm (0.0065 ft) per year is equivalent to a real shoreline recession Δx_r of 9 cm (0.3 ft) per year, which in accordance with Bruun's rule does not add to the flux of sediment in the control cell (see Section 9.5).

(4) The budget is first summed without the contribution from the shoreline flux-volume Q_f because of uncertainty in the flux-surface height (or closure height) Z. Then, the estimated shoreline change $\partial X/\partial t$ is computed from equations 9.2 and 9.3, using a value of Z = 14 m (45 ft). This value of Z is applicable to the usual seasonal changes that prevail during periods between high total-energy events (i.e., Figure 9-12). It is used here only for comparing the different budgets. When corrected for sealevel rise Δx_r, $\partial X/\partial t$ can be compared with measurements of shoreline change over the period of observation.

(5) The budget is considered to balance when the shoreline change rate $\partial X/\partial t$, computed from the volume-flux $Q_f \equiv -\partial V/\partial t$, is less than 3 cm/yr (0.1 ft/yr).

Natural Conditions circa 1900-1938

The budget for the three subcells under natural conditions is shown in Table 9-12. It is assumed that there is no longshore transport into the north subcell ($Q_{\ell 1}$ = 0), whereas the longshore transport out of the north subcell $Q_{\ell 2}$ is assumed to be 2/3 of the longshore transport rate determined for the uniform period at Oceanside of 190,000 cubic meters per year (254,000 yd^3/yr). This estimate of the longshore transport is based on the relation between transports at Oceanside, San Onofre and San Clemente as shown in Figure 9-8. In addition, the budget assumes that there is a coastal longshore transport Q_n outside of the surfzone, in accordance with the known seasonal and longshore transport on the shorerise. As discussed in (2) above, this transport is assumed to be 10% of the longshore transport Q_ℓ.

The yield from the coastal blufflands into the north subcell is assumed to be ½ the rate measured at San Onofre State Park. The offshore transport onto the shelf due to downwelling Q_o is assumed to be that determined from comparison of the hydrographic charts of 1934 and 1971/72 as listed in Table 9-5. The yield from the San Juan and San Mateo Creeks (Q_r) is listed in Table 9-7. The data sources for the sediment contributions and losses in each subcell are referenced in footnotes to each table.

These first order calculations indicate that the inputs and outputs are essentially in balance. The results suggest that the estimates were reasonable and that there was little net change in position of the shoreline during this period. The largest difference between input and output occurs in the central subcell for which a positive value of 125,000 cubic meters (165,000 yd^3) per year is calculated. When entered into equation (9-2) for shoreline change, and using a flux-surface height Z = 14 m (45 ft), the value of $\partial X/\partial t$ indicates a net shoreline accretion for all three subcells.

The implied net shoreline accretion (Table 9-12) of 3, 23 and 18 cm/yr (0.1, 0.8 and 0.6 ft/yr) for the three subcells appear to fall within the limits of accuracy. However, assuming other budget quantities balance, sealevel rise would result in a shoreline recession of 9 cm (0.3 ft) per year. This implies that the sediment input to the cells, in the presence of a known sealevel rise and its associated potential for shoreline recession, was equivalent to a shoreline accretion of $\partial X/\partial t$ plus $\triangle x_r$ of 12, 32 and 27 cm (0.4, 1.1 and 0.9 ft) per year. Over a decade or two, this would provide a significant widening of the beaches, a situation that apparently did not occur for this period except at river mouths following floods. This "natural" balance suggests that the

TABLE 9-12
OCEANSIDE LITTORAL CELL
NATURAL PRE-DAM CONDITIONS 1900-1938
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcell					
	North ℓ = 14 km		Central ℓ = 38 km		South ℓ = 32 km	
	Input	Output	Input	Output	Input	Output
Q_{ℓ}[a]	0	130	130	190	190	0
Q_n[b]	0	15	15	20	20	0
$Q_{b,o}$[c]	130	45	400	490	150	180
Q_a	0	0	0	0	0	0
$Q_{r,s}$[d]	65	0	210	0	50	220
Total	+195	-190	+755	-700	+410	-400
Net ($\partial V/\partial t$)	+5		+55		+10	
$\partial X/\partial t$ (m/yr)[e]	0.03 accretion		0.10 accretion		0.02 accretion	

[a] From Inman & Jenkins (1983) (see Chapter 6), north subcell 2/3 Oceanside (Figure 9-8).

[b] Assumed to be 10% of Q_{ℓ}.

[c] $Q_{b\ell}$ (north) assumed to be ½ the rate measured for San Onofre (Table 9-6); $Q_{b\ell}$ = 9 m^3/—yr) x 14 km.
$Q_{b\ell}$ (central) assumed to be average of San Onofre and Camp Pendleton (Table 9-6); $Q_{b\ell}$ = 15 m^3/(—yr) x 38 km.
$Q_{b\ell}$ (south) assumed to be Torrey Pines Park (Table 9-6); $Q_{b\ell}$ = 7 m^3/(—yr) x 32 km.
Q_{o2} from Table 9-5; assuming downwelling rates of 3.2, 13 and 5.5 m^3/(—yr), respectively.

[d] $Q_{r\ell}$ from Table 9-7; increased yield for Central subcell due to flood of 1916.
Q_{s2} from Inman & Jenkins (1983), plus Q_n.

[e] From equations 9-2 and 9-3 for Z = 14 m. This relation does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

yield of bluffland and/or river sediment is overestimated. In view of the uncertainty in datum in comparing the 1889 and 1968 bluffland surveys, the yield of bluffland material seems to be the suspicious quantity. Accordingly, in the following budget analysis, the estimates of the yield of bluffland material is reduced to 70% of that listed in Table 9-6 and shown in Table 9-12.

Mild, Uniform Northwesterly Wave Climate circa 1960-1978

This period of uniform wave climate was also one of unprecedented coastal development along the Oceanside Littoral Cell. The period saw the rapid urbanization of coastal blufflands, the development of two harbors (Oceanside and Dana Point), two coastal power plants (Encinas at Agua Hedionda Lagoon and the San Onofre Nuclear Power Plant), and the construction of numerous groins, jetties, seawalls and cliff-edge residences. While the yield of sediment from streams decreased due to construction of dams on rivers, large volumes of sand were excavated from the coastal blufflands and lagoons and placed on the beach. Urbanization has increased the yield of sediment by runoff from the coastal bluffland (State Coastal Conservancy, 1989), although there are no quantitative estimates of this increase (Kuhn, et al., 1987: CCSTWS 87-2).

Beach nourishment, bypassing, and sand entrapment behind structures complicate analysis of the budget by introducing many "credits" and "deficits" that vary in time and place. In addition, there is always a time and distance lag associated with the downcoast propagating accretion and erosion waves caused by the release and entrapment of littoral material. The residence time for these waves to traverse a given subcell was estimated from Inman (1987) and used in establishing the budget in Table 9-13 (e.g., footnote c).

The harbor excavation and bypass procedures at Oceanside Harbor present the single most complex problem in interpreting the budget for this period. Accordingly, it is treated in greater detail below. The longshore transport rate Q_ℓ is that from the detailed evaluation of Inman & Jenkins (1983), and the longshore transport outside the surfzone Q_n is taken as 0.1 Q_ℓ in accordance with budget analysis assumption (2). The yield of sediment from the blufflands Q_b is from Table 9-6, but it is reduced to 70% of the value in the previous budget (Table 9-12) as this estimate appears too high under natural conditions. The river contributions Q_r are from Table 9-7, using the present post-dam stream conditions. Further details for the budget quantities are given in the footnotes to Table 9-13.

The effects of Oceanside Harbor are shown in the lower portion of Table 9-13 and the types of transport and their paths in Figure

TABLE 9-13
OCEANSIDE LITTORAL CELL
UNIFORM NW WAVE CLIMATE CIRCA 1960-1978
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcell					
	North 14 km		San Mateo Pt to Harbor 27 km		South 32 km	
	Input	Output	Input	Output	Input	Output
Q_ℓ [a]	0	130	130	190	190	0
Q_n [a]	0	15	15	20	20	0
$Q_{b,o}$ [b]	90	45	280	350	150	180
Q_a [c]	90	0	50	0	75	0
$Q_{r,s}$ [d]	45	0	20	0	5	220
Total	+225	-190	-495	-560	+440	-400
Net ($\partial V'/\partial t$)	+35		-65		+40	
$\partial X/\partial t$ (m/yr) [e]	0.18 accretion		0.17 erosion		0.09 accretion	

Harbor Effects	Harbor to Carlsbad Submarine Canyon 11 km	
Q_ℓ [a]	190	190
Q_n [a]	20	20
$Q_{\ell d}$ [f]	0	40
$Q_{\ell t}$ [f]	0	150
Q_{nd} [f]	0	20
$Q_{ab,at}$ [f]	230	80
Subtotal (harbor effects)	+440	-500
$Q_{b,o}$ [b]	120	140
Q_a [c]	75	0
Q_r [d]	30	0
Total	+665	-640
Net ($\partial V'/\partial t$)	+25	
$\partial X/\partial t$ (m/yr) [e]	0.16 Accretion	

TABLE 9-13 (CONTINUED)
FOOTNOTES

[a] Q_ℓ, Q_n same as Table 9-12.

[b] Q_b 70% that in Table 9-12 in accordance with findings from "natural" budget (see last paragraph of text).
Q_o same as Table 9-12.

[c] $Q_{a\ell}$ (north 1.8 x 10^6 m^3 nourishment at Capistrano Beach 1964 1970 averaged over 20 yr = 90 x 10^3 m^3/yr (Chapter 6).

$Q_{a\ell}$ (central, north 27 km) 1.0 x 10^6 m^3 excavated from bluff at San Onofre Power Plant 1964-Dec 1984, averaged over 20 yr = 50 x 10^3 m^3/yr (Flick & Wanetick, 1989).

$Q_{a\ell}$ (central, south 11 km) 1.1 x 10^6 m^3 excavated from Oceanside Harbor basin 1962/63 averaged over 15 yr = 75 x 10^3 m^3/yr (Table 9-14).

$Q_{a\ell}$ (south) 3.1 x 10^6 m^3 excavated from Agua Hedionda Lagoon in 1954, assuming residence time in subcell 16 yr (Inman, 1987), providing ½ total averaged over 20 yr from 1960-1979, equals 75 x 10^3 m^3/yr.

[d] $Q_{r\ell}$ from Table 9-7; Q_{s2} is sum of the canyon head loss (Inman & Jenkins, 1983) and the longshore transport along the shorerise, Q_n.

Q_{s2} from Inman & Jenkins (1983), plus Q_n.

[e] From equations 9-2 and 9-3, for Z = 14 m. This relation does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

[f] Harbor effects shown in Figure 9-17 and described in text.

9-17 and Table 9-11. The harbor effects include deflection of the longshore currents $Q_{\ell d}$ and Q_{nd} and harbor trapping $Q_{\ell t}$ as well as the artificial bypassing Q_{ab} and the estimated quantity of bypassed material retrapped in the harbor Q_{at}. These harbor effects and their transport paths are discussed and evaluated in Inman & Jenkins (1983).

Note that the harbor effect is obtained by dividing the central subcell into two portions at the harbor and including the harbor effects as an internal subtotal of the southern 11 km (7 mi) of the subcell extending from the harbor to Carlsbad Submarine Canyon. Table 9-14 shows that the rate of dredging material from the harbor and bypassing to the downcoast beaches from the harbor enlargement between 1960 and circa 1980 was about 230,000 m^3/yr (300,000 yd^3/yr). This value is entered as Q_{ab} in Table 9-13. The input to the harbor complex from upcoast is $Q_{\ell 1}$ and $Q_{n\ell}$ or an estimated total of 210,000 m^3/yr (275,000 yd^3/yr). The output from the harbor complex is the bypass rate Q_{ab} minus that portion of the bypass that is retrapped in the harbor Q_{at} or a total of 150,000 m^3/yr (200,000 yd^3/yr). Therefore this tabulation indicates that the harbor has caused a net loss of about 60,000 m^3/yr (80,000 yd^3/yr) during this period.

Table 9-13 provides a more detailed analysis of elements contributing to the harbor effect, but note that the algebraic sum of the internal subtotal is also -60,000 m^3/yr (-80,000 yd^3/yr). This net loss of sand associated with the harbor appears to be in agreement with the extensive shorezone erosion downcoast from the harbor during this period. The erosion was partially repaired by a dry haul of 700,000 m^3 (920,000 yd^3) from the San Luis Rey River bed which was placed on the beaches between November 1981 and May 1982 (Table 9-14).

The only beaches that underwent serious erosion during this time period were Capistrano Beach and Oceanside Beach south of the harbor. Both of these beaches received large amounts of artificial nourishment. Elsewhere the beaches generally widened during this period, except Torrey Pines Beach which eroded as the erosion wave from the harbor propagated downcoast, and then widened following the arrivals of the accretion waves.

In view of the relatively high rates of artificial nourishment, it is surprising that the beach accretion was not greater. The artificial nourishment for the north, central, and south subcells was sufficient, using a flux-surface height Z = 14 m (45 ft), to widen the beaches at a rate of 0.5, 0.2, and 0.2 m/yr (1.5, 0.6, and 0.6 ft/yr), respectively, yet this did not happen.

Inspection of the budget for the central subcell implies slight erosion north of the harbor and accretion south of the

TABLE 9-14

SUMMARY OF QUANTITIES OF DREDGED MATERIAL FOR OCEANSIDE HARBOR AND BEACH

Starting Date	Completion Date	Disposal Area	Approx. Dredge Quantity, yd^3	Cum. Beach Nour. (10^6 yd^3)
May 1942	Aug 1944	Inland fill	1500000	0
Apr 1945	Jun 1945	Inland fill	219000	0
Apr 1957	May 1958	6th to 9th St.	800000	0.8
Aug 1960	Aug 1960	6th to 9th St.	17500	
Sep 1960	Oct 1960	6th to 9th St.	23700	0.84
Jan 1961	May 1961	6th to 9th St.	222350	
Aug 1961	Dec 1961	6th to 9th St.	258800	1.32
Mar 1962	Feb [a]	9th St. to Loma Alta Creek	3810700	5.13
Aug 1965	Aug 1965	9th to 3rd St.	111400	5.24
Mar 1966	Apr 1966	3rd St. to Minnesota Ave.	684000	5.93
Jul 1967	Jul 1967	3rd to Tyson St.	177900	6.11
Mar 1968	Jun 1968	San Luis Rey to Wisconsin Ave.	433900	6.54
Jul 1969	Sep 1969	San Luis Rey to 3rd St.	353000	6.89
Apr 1971	Jul 1971	3rd St. to Wisconsin Ave.	551900	7.44
Jun 1973	Jul 1973	Tyson to Hays St.	434100	7.88
Oct 1974	Jan 1975	Pine to Witherby St.	559750	8.44
May 1976	Jul 1976	Ash to Witherby St.	550000	8.99
Aug 1977	Feb 1978	Ash to Witherby St.	318550	9.31
Feb 1981	Jun 1981	3rd St. to Buccaneer	463000	9.77
Nov 1981	May 1982 [b]	Oceanside Beaches	920000	10.69
		SUBTOTAL in cubic yards	12409550	10.69
		SUBTOTAL in cubic meters	9493000	8.18
1984	1984	Oceanside Beaches	475000	11.17
1986	1986	Oceanside Beaches	450000	11.62
1988	1988	Oceanside Beaches	220000	11.84
		TOTAL in cubic yards	13554550	11.84
		TOTAL in cubic meters	10638000	9.1

[a] 1.1×10^6 m^3 (1.4×10^6 yd^3) new excavation from harbor basin, 1.8×10^6 m^3 (2.4×10^6 yd^3) from littoral entrapment by 1942-1958 construction.

[b] Dry haul from San Luis Rey River 705,000 m^3.

Source: Inman & Jenkins (1983) and USACE LAD, in-house records.

harbor. Actually, observation of beach changes (Chapter 3) suggest just the opposite. This may mean that the budget underestimates the effect of the harbor. Perhaps the downwelling Q_{o2} north of the harbor is less than estimated, whereas deflection at the harbor is greater than estimated. These considerations emphasize the need for a more extensive study of the harbor effect.

Variable Westerly Wave Climate of 1983-1990

The relatively mild and seasonably predictable wave climate of the "uniform epoch" of 1945-1978 was terminated by a period of more variable and at times far more intense wind and wave events of the winters of 1979/80 and 1982/83. The latter was particularly severe with repeated series of cluster storms. These cluster storms produced extensive erosion of the shorezone with downwelling of sediment across the gentle toe of the shorerise and onto the steeper slopes of the 10-fathom terrace, where it remains lost to the shorezone sedimentation cycle.

The three beach profiles north of Oceanside Harbor (PN1180-1280, Table 9-10) indicate that the average loss of sediment from the shorezone to a depth of 13 m MSL was 860 m^3 per meter of shoreline (1030 yd^3/yd of shoreline). The beaches south of the harbor had just received 704,000 m^3 (920,000 yd^3) of sand in May 1982, dry hauled from the San Luis Rey River bed (Table 9-14). This material was removed from near the surfzone by the storms and deposited along the shorerise and in deeper water.

The period following the cluster storm epoch of 1982/83 has been unusually variable and dry. Further, the wave climate has changed. Much more energy comes from the south, in some cases reversing the usual net southerly longshore transport into a net northerly component (Figure 9-8). These conditions suggest, on average, that the net southerly component of longshore transport Q_ℓ is only about one-quarter of its former value. Further, analysis of profiles shows that most sand movement on the beach is of the seasonal type with closure depth h_c extending to about 10 m (33 ft) MSL, as opposed to depths in excess of 13 m (43 ft) MSL for the previous periods which included high total-energy events. This suggests that little material has been lost offshore by downwelling (Q_{o2} = 0). Therefore, although input from coastal blufflands may be less due to the drought (say one-half of the former value), the net balance for this short period is one of accretion.

Estimates for the budget of sediment for the 1983-1990 period of variable, but dry weather are shown in Table 9-15. Criteria in arriving at the estimates are listed in the footnotes and discussed above. All subcells show shoreline accretion associated with the replenishment of sand in the shorezone following the high total-energy storms of 1982/83. Even though the yield of sediment

TABLE 9-15
OCEANSIDE LITTORAL CELL
VARIABLE W WAVE CLIMATE CIRCA 1983-1990
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcell					
	North ℓ = 14 km		San Mateo Pt to Harbor ℓ = 27 km		South ℓ = 32 km	
	Input	Output	Input	Output	Input	Output
Q_ℓ[a]	0	35	35	50	50	0
Q_n[a]	0	5	5	5	5	0
$Q_{b,o}$[b]	45	0	140	0	75	0
Q_a[c]	0	0	25	0	0	0
$Q_{r,s}$[d]	0	0	0	0	0	55
Total	45	-40	205	-55	130	-55
Net ($\partial V'/\partial t$)	+5		+150		+75	
$\partial X/\partial t$ (m/yr)[e]	0.03 accretion		0.40 accretion		0.17 accretion	

Harbor Effects	Harbor to Carlsbad Submarine Canyon 11 km	
Q_ℓ[a]	50	50
Q_n[a]	5	5
$Q_{\ell d}$[f]	0	10
$Q_{\ell t}$[f]	0	40
Q_{nd}[f]	0	5
$Q_{ab,at}$[f]	125	85
Subtotal (harbor effects)	180	-195
$Q_{b,o}$[b]	60	0
Q_a[c]	0	0
Q_r[d]	0	0
Total	240	-195
Net ($\partial V'/\partial t$)	+45	
$\partial X/\partial t$ (m/yr)[e]	0.29 accretion	

TABLE 9-15 (CONTINUED)
FOOTNOTES

[a] Southerly shift in wave direction reduces Q_ℓ and Q_n to 25% of the 1960-1979 estimated value shown in Table 9-13 (refer to Figure 9-8 and text).

[b] Drought reduces $Q_{b\ell}$ to 50% of the 1960-1979 rate in Table 9-13. Q_{02} is negligible due to absence of high total-energy events.

[c] San Onofre December 1984 release of 168 x 10^3 m^3 new source material (Flick & Wanetick, 1989) averaged over 7 yr = 25 x 10^3 m^3/yr.

[d] River yield assumed negligible ($Q_{r\ell}$ = 0); Q_{s2} assumed to be equal to $Q_{\ell 1}$ + $Q_{n\ell}$.

[e] From equations 9-2 and 9-3, for Z = 14 m. This does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

[f] Q_{ab} from Table 9-14, 876 x 10^3 m^3 averaged over 7 yr = 125 x 10^3 m^3/yr. Harbor effects identified in Figure 9-17 and described in text.

from blufflands and rivers has decreased from the previous period as shown in Table 9-13, downwelling was absent, and longshore transport was considerably reduced. The result is a net accretion of the shorezone of the entire cell.

Accretion in the north subcell was slow, but all other subcells showed substantial recovery. Including the correction for sealevel rise, the accretion rates in terms of shoreline advance were about 0.5, 0.4, and 0.3 m (1.6, 1.2, and 1.0 ft) per year for the central subcell north and south of the harbor and the south subcell, respectively. Although the north subcell appears from these figures to have recovered the least, it is likely that the increased northerly component of the longshore transport has moved some sand released from the San Onofre nourishment north into the north subcell. This contention is supported by the nearly equal north and south components of longshore transport shown in Figure 9-8 and by the observations of Flick & Wanetick (1989).

9.6.2 Predictions for the Future Condition of the Cell

The preceding analysis of the budget of sediment for the Oceanside Littoral Cell shows that the "health" of the beaches has been closely related to the type of wave climate and the degree of human intervention. Episodic, high total-energy storm events result in extensive denuding of the beaches and transport of shorezone sand onto the steep shelf where it is lost to the beach. The beaches are replenished with sand during prolonged periods where mild wave climate is associated with influxes of sediment from rivers and the erosion of blufflands. Beach replenishment is enhanced by a wave climate that reduces the net longshore transport, a condition that prevailed from 1983 to 1990.

Human intervention has diverse effects on the beach. Urbanization has resulted in seawalls that take up beach space and increase beach erosion. Urbanization also has vastly increased the yield of sediment from blufflands which nourishes the beaches. This sediment has become an increasingly important source of material as it replaces sediment that is now trapped behind dams on rivers. Harbor projects such as that at Oceanside seriously interfere with the natural beach processes, often resulting in severe downcoast erosion. On the other hand, "new source" material from these projects has a mitigating effect when placed on the beach as nourishment

Between 1954 and 1988, 20 million m^3 (26 million yd^3) of material was placed on the beaches of the Oceanside Littoral Cell, and 8 million m^3 (12 million yd^3) of this material was "new source" material excavated from the seacliffs and blufflands and dredged from lagoon sediments of Holocene and older age. Consideration of equation 9-2 shows that this "new source" beach nourishment should have been sufficient to extend the mean shoreline of the entire 84 km (52 mi) length of the cell a seaward distance of 7 m (25 ft), assuming a shoreline flux-surface height Z = 14 m = 45 ft. In spite of this massive nourishment project, there is little evidence of it on the beaches of today. Some of this material has been lost by harbor deflection; some has been lost down submarine canyons; and some has been lost to the deeper shelf by downwelling.

9.7 MISSION BAY LITTORAL CELL

This compartment extends along the coast for 22 km (14 mi) from Point La Jolla to Point Loma. It includes 5.8 km (3.6 mi) of picturesque pocket beaches along the La Jolla headland (Point La Jolla subcell) and 9.7 km (6.0 mi) of rocky cliffs along the Point Loma headland (Point Loma subcell). Seven km (4.4 mi) of sandy beach, extending from False Point to Narragansett Street south of the Municipal Pier at Ocean Beach, form the sand spits and sand beaches of the Mission Beach and Ocean Beach subcells.

The natural source of sediment for the Mission Bay Cell was the San Diego River which flowed alternately to either side of the Point Loma headland, sometimes into Mission Bay (False Bay) and sometimes into San Diego Bay (Brooks, et al., 1948). During significant floods, the river flowed through Mission Bay depositing some material in the ocean. There, ebb-tidal currents from Mission Bay and ocean currents transported some sand south along the rocky coast of Point Loma. Under such conditions, some material probably "leaked" around Point Loma and into the Silver Strand Littoral Cell. In 1876 the U.S. Army Corps of Engineers built a dike that permanently channeled the river flow into Mission Bay. However, the many dams on the San Diego River prevent it from being a significant present-day source of sediment (Table 9-7). The dams on the San Diego River include those for Murray Reservoir (1918), El Capitan Reservoir (1935), and the Chet Harriet Reservoir (1962).

The most significant structural modification of the shoreline occurred during 1948 to 1950 when three jetties for navigation and river flood control were constructed at the entrance to Mission Bay. The south and middle jetties were extended to their present length in 1970. Between 1948 and 1984, dredging within the bay and from the entrance channel has resulted in "new source" sand nourishment for the beaches of Mission Beach and Ocean Beach of a total of 1,012,000 m^3 (1,323,000 yd^3).

Unfortunately, the beach profiles available for the Mission Bay Cell are not very informative. Bruun (1954) studied a series of six ranges along Mission Beach each measured four times during 1950. He concluded that Mission Beach was a stable, conservative system, losing little material to the north or south. Two of the four Corps of Engineers' historical beach profiles date back to 1949 and 1951 for survey depths of 12 m (40 ft) MLLW (Table 9-9: MB340, OB230), but no measurements were taken during the five years preceding the 1982/83 storms. Furthermore, the profiles Bruun studied did not include any of the historical profiles. Thus, the profiles are not particularly helpful for evaluating storm effects of 1939, 1982/83, and 1988, or the beach changes directly associated with the jetty building of 1948/50.

However, the pronounced changes in bathymetry between 1934 and 1970 shown in Figure 9-5 suggest that the tropical storm of September 1939 moved vast quantities of sediment along the shores of the Mission Bay Cell. Generally, there is deepening off the Mission Bay entrance channel and shoaling at the points. These bathymetric changes probably indicate erosion of the submerged portions of the Mission Bay/San Diego River delta and northward transport of material to the shelf off La Jolla (see Section 9.2.2).

The volume changes on the historic profiles show large changes at Mission Beach of about 300 m^3/m of beach (360 yd^3/yr), and even greater at Ocean Beach. Contrary to short-term studies (Bruun, 1954), at times there appear to be appreciable beach changes. Over the period of the historic profiles, and to depths of 40 ft MLLW, two of the three Mission Beach profiles (Appendix F; MB384, MB310) show a net loss. The only Ocean Beach profile near the jetties (OB230) shows a net gain.

9.7.1 Analysis of the Budget of Sediment

As indicated above, there is insufficient data to attempt the same detailed analysis for the Mission Bay Cell that was performed for the Oceanside Littoral Cell. Everts & Bertolotti (1988: CCSTWS 88-7) provide a comprehensive discussion of what is known about the budget. Much of the present analysis is drawn from their work, and we apply assumptions (1) through (5) as listed in Section 9.6.1.

The four subcells and their potential types of credit and debit are shown in Figure 9-18. The north (Point La Jolla) and south (Point Loma) subcells are "cliffed" coast with numerous small pocket beaches. Some aspects of the Point La Jolla pocket beaches are described in Inman (1953) where it is shown that the source of sand is from the erosion of the sandstone cliffs of Cretaceous age (>70 million years), and no sand from the Oceanside Littoral Cell migrates to the Point La Jolla beaches.

It seems likely that during intense storms from the south, shelf material may be carried north into La Jolla Submarine Canyon. During storms from the north, some material may be carried around Point Loma. However these events are probably episodic.

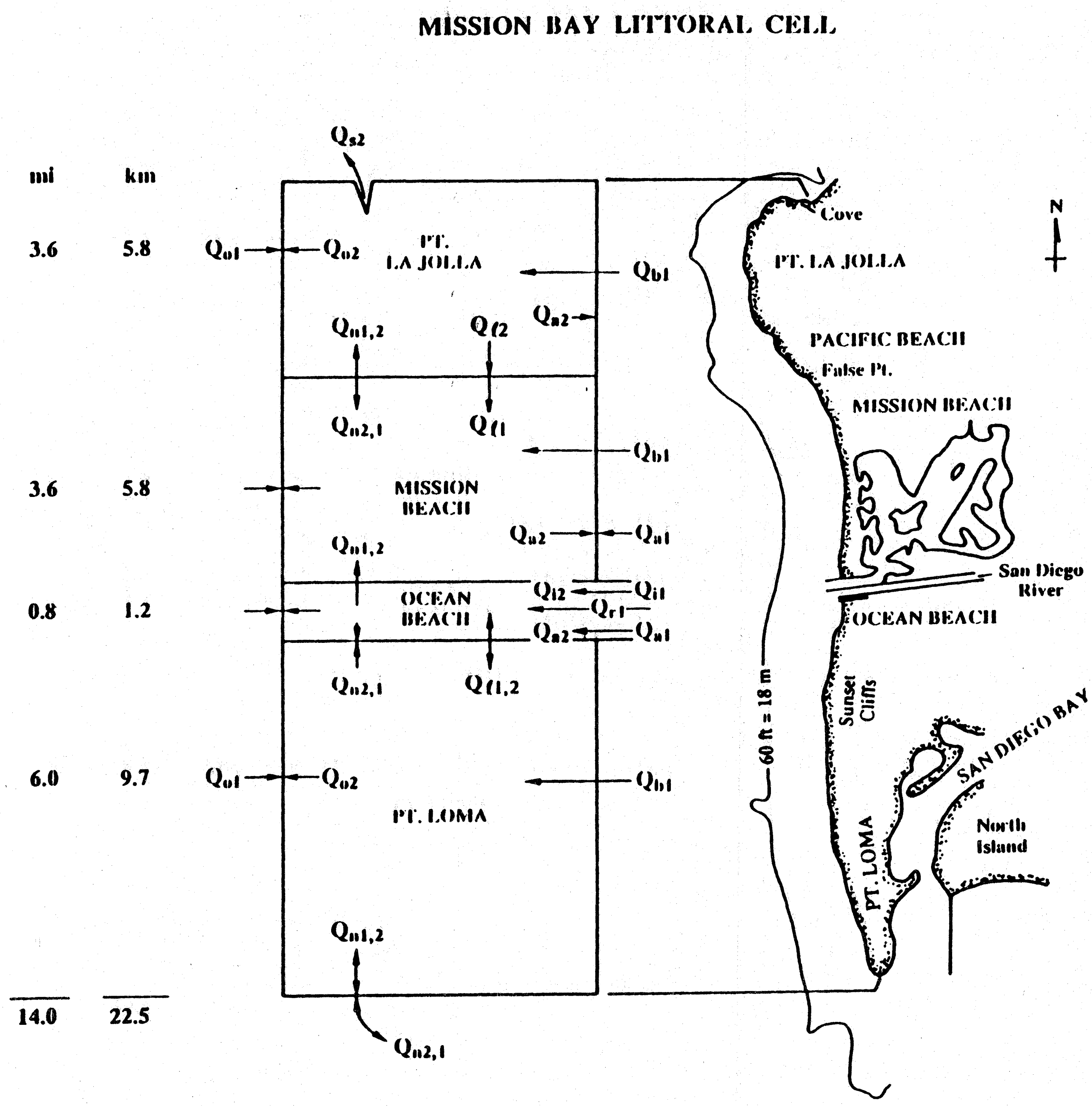


Figure 9-18. Elements of the sediment budget for Mission Bay Littoral Cell and its four subcells. Symbols are defined in Table 9-11.

Uniform Northwesterly Wave Climate circa 1960-1978

Extensive sandy beach areas are restricted to the 7.0 km (4.4 mi) length of the Mission Beach and Ocean Beach subcells. The budget compiled here considers the period following the construction of the Mission Bay Jetties until the cluster storms of 1982/83.

Table 9-16 shows that the budget is dominated by the artificial beach nourishment, Q_a estimated at 25,000 m^3 (19,000 yd^3) and 10,000 m^3 (7,600 yd^3), placed in Mission Beach and Ocean Beach subcells. After subtracting the recession due to sealevel rise, this material accounts for the overall beach accretion of 9 cm/yr (0.3 ft/yr) and 21 cm/yr (0.69 ft/yr) in the two cells, respectively. Even so, mining of beach sand during kelp removal operations is clearly a significant problem (refer to Table 9-16, footnote c).

Variable Westerly Wave Climate circa 1983-1990

The amount of shoreline change during five summer to winter seasonal cycles at Mission Beach from 1979 through 1986 are shown by Thompson (1987). The greatest change, averaging about 30 m (100 ft) recession at MHW, was between October 1982 and April 1983, reflecting the effects of the 1982/83 cluster storms. The historical beach profiles show that the beach gradually recovered over a period of years. Although the cluster storms caused downwelling of sediment onto the shelf (Q_{o2}), the gentle slope of the Mission Bay shelf permitted wave action to return this material gradually to the beach areas of the cell.

The budget for this period (Table 9-17) indicates a nearly stable shoreline, but with some excess material in the Point Loma subcell, probably near the south end of the point. Nearly all of the sediment input is from cliff erosion, with only small amounts from the San Diego River. In view of the long-term loss of beach due to sealevel rise, it is apparent that additional sand sources must be found for the future.

9.7.2 Predictions for the Future

None of the values entered in Tables 9-16 and 9-17 is thought to have a high level of reliability. Every value is a simple estimate, and the budget of sediment calculated in this study should be considered at best a guide to further study of the Mission Bay Cell. Nor are the significant variables affecting the future budget of the Mission Bay Cell quantified with any certainty.

The forecast by Everts and Bertolotti (1988: CCSTWS 88-7) provides the most recent, comprehensive treatment for the Mission

TABLE 9-16
MISSION BAY LITTORAL CELL
UNIFORM NW WAVE CLIMATE CIRCA 1960-1978
SEDIMENT BUDGET IN 10^3 m^3/yr

	Point La Jolla ℓ = 5.8 km		Sandy Beach Subcells: Mission Beach ℓ = 5.6 km		Sandy Beach Subcells: Ocean Beach ℓ = 1.2 km		Point Loma ℓ = 9.7 km	
	Input	Output	Input	Output	Input	Output	Input	Output
Q_ℓ[a]	0	0	0	0	0	0	0	0
Q_n[a]	0	5	5	5	5	10	10	10
$Q_{b,o}$[b]	10	0	0	0	0	0	20	10
Q_a[c]	0	0	25	10	10	5	0	0
$Q_{r,s}$[d]	0	5	5	0	10	0	0	0
Q_i[f]	0	0	0	5	0	5	0	0
Total	10	-10	35	-20	25	-20	30	-20
Net ($\partial V'/\partial t$)	0		+15		+5		+10	
$\partial X/\partial t$ (m/yr)[e]			0.18		0.30			
	balance		accretion		accretion		accretion	

TABLE 9-16 (CONTINUED)
FOOTNOTES

[a] Q_ℓ is zero because of pocket beaches on the headlands and blocking of longshore transport at the Mission Bay jetties.

Q_n There is probably a southerly transport outside the surfzone during this period of predominant northwesterly waves. This may account for some accretion off Point Loma and a transport around Point Loma and into the Mission Bay Entrance Channel.

[b] Q_b Assuming cliff and blufflands erosion contribute 2 m^3/m-yr to the rocky coasts of Point La Jolla and Point Loma. This may be too high, although comparison with Table 9-6 suggests not.

Q_o It is likely that some sand is lost to the shelf off Point Loma

[c] $Q_{a\ell}$ (Mission Beach) 938 x 10^3 m^3 placed on beach over 36 year period 1948 to 1984

$Q_{a\ell}$ (Ocean Beach) 285 x 10^3 m^3 placed on beach over 34 year period 1950 to 1984

Q_{a2} (Point La Jolla) unknown amount removed with kelp

Q_{a2} (Mission Beach) 10 x 10^3 m^3/yr removed with kelp (Hotten, 1988)

Q_{a2} (Ocean Beach) 2 x 10^3 m^3/yr removed with kelp (Everts & Bertolotti, 1988: CCSTWS 88-7, rounded to 5 x 10^3 m^3/yr

[d] $Q_{r\ell}$ estimated yield of 15 x 10^3 m^3/yr (Table 9-7) assuming 1/3 to Mission Beach, 2/3 to Ocean Beach

Q_{s2} assume storms cause attrition onto steep slopes of La Jolla Submarine Canyon

[e] From equations 9-2 and 9-3, for Z = 14 m. This does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

[f] Q_{i2} deposition between jetties and in entrance channel, balanced by $Q_{i\ell}$ which is included in $Q_{a\ell}$.

TABLE 9-17
MISSION BAY LITTORAL CELL
VARIABLE W WAVE CLIMATE CIRCA 1983-1990
SEDIMENT BUDGET IN 10^3 m^3/yr

	Point La Jolla ℓ = 5.8 km		Sandy Beach Subcells: Mission Beach ℓ = 5.6 km		Sandy Beach Subcells: Ocean Beach ℓ = 1.2 km		Point Loma ℓ = 9.7 km	
	Input	Output	Input	Output	Input	Output	Input	Output
Q_{ℓ}[a]	0	0	0	0	0	0	0	0
Q_n[a]	0	0	0	0	0	0	0	0
$Q_{b,o}$[b]	10	0	0	0	0	0	20	10
Q_a[c]	0	0	5	10	0	5	0	0
$Q_{r,s}$[d]	0	10	5	0	10	0	0	0
Q_i[f]	0	0	0	5	0	5	0	0
Total	10	-10	10	-15	10	-10	20	-10
Net ($\partial V'/\partial t$)	0		-5		0		+10	
$\partial X/\partial t$ (m/yr)[e]			0.06		0			
	balance		erosion		balance		accretion	

TABLE 9-17 (CONTINUED)
FOOTNOTES

[a] Q_ℓ, Q_n are zero because of shift to net westerly wave approach during this period.

[b] Q_b Assuming cliff and blufflands erosion contribute 2 m^3/m-yr to the rocky coasts of Point La Jolla and Point Loma. This may be too high, although comparison with Table 9-6 suggests not.

[c] $Q_{a\ell}$ material placed on Mission Beach 1984, averaged over this period.

Q_{a2} (Point La Jolla) unknown amount removed with kelp.

Q_{a2} (Mission Beach) 10 x 10^3 m^3/yr removed with kelp (Hotten, 1988).

Q_{a2} (Ocean Beach) 2 x 10^3 m^3/yr removed with kelp (Everts & Bertolotti, 1988: CCSTWS 88-7, rounded to 5 x 10^3 m^3/yr).

[d] $Q_{r\ell}$ estimated yield of 15 x 10^3 m^3/yr (Table 9-7) assuming 1/3 to Mission Beach, 2/3 to Ocean Beach.

Q_{s2} assume increased high waves of this period cause greater attrition onto steep slopes of La Jolla Submarine Canyon.

[e] From equations 9-2 and 9-3, for Z = 14 m. This does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

[f] Q_{i2} deposition between jetties and in entrance channel, balanced by $Q_{i\ell}$ which is included in $Q_{a\ell}$.

Bay Cell. The following recommendations are summarized from their study.

Shoreline erosion is predicted for the Mission Beach Subcell (12 cm/yr, 0.4 ft/yr) and the Ocean Beach Subcell (88 cm/yr, 2.9 ft/yr) despite projected nourishment equivalent to the 1960-1986 rate. Loss of sand to the entrance channel was expected to continue at the same rate as in the past. Due to the anticipated increase in rate of sealevel rise (averaging 70 cm = 2.3 ft per century, EPA low, mid-range scenario), shoreline retreat will increase with time. Sediment discharge from the San Diego River will likely decline over the next 50 years, reducing the natural source for the Ocean Beach Subcell.

Consequently, in order to maintain a stable shoreline, the need for sand nourishment to the beaches will increase in the future. Through year 2037, approximately 420,000 m^3 (550,000 yd^3) of "new source" sediment will be needed in the Mission Beach Subcell, and 610,000 m^3 (790,000 yd^3) will be required in the Ocean Beach Subcell to maintain the 1987 shoreline. The supply of sand nourishment to the Ocean Beach Subcell will have to be significantly increased over present amounts, and additional sources of fill other than from the entrance channel will have to be utilized.

All of the sediment volumes suggested above for beach nourishment are dependent upon the estimated rate of sealevel rise. Management of the cell's sand resources will require monitoring of the rate of sealevel rise at least every 10 years in order to update beach replenishment needs.

9.8 SILVER STRAND LITTORAL CELL

This littoral cell extends for 26 km (16 mi) from Point Loma to the United States/Mexico Boundary and south for many miles along the coast of Baja California, Mexico (Figure 9-19). The cell includes 22 km (14 mi) of sandy beach extending from Zuñiga Jetty at the entrance to San Diego Bay to the international border. The Mexico portion of the cell appears to extend about 30 km (20 mi) below the border to Punta El Descanso, or farther, but has never been studied in detail. The first 4.5 km (2.8 mi) of the Mexican portion of the cell, known as Playas de Tijuana, consists of sandy beaches backed by seacliffs (Figure 9-19).

This is one of the few cells in southern California with a significant northerly transport of sand, caused by the wave shadow in the lee of Point Loma. Under natural conditions, the principal source of sediment was the Tijuana River which brought material to the coast just north of the border. Bifurcation of the sediment transport path from the delta of the Tijuana River nourished the beaches to the south and provided the sand for the Silver Strand

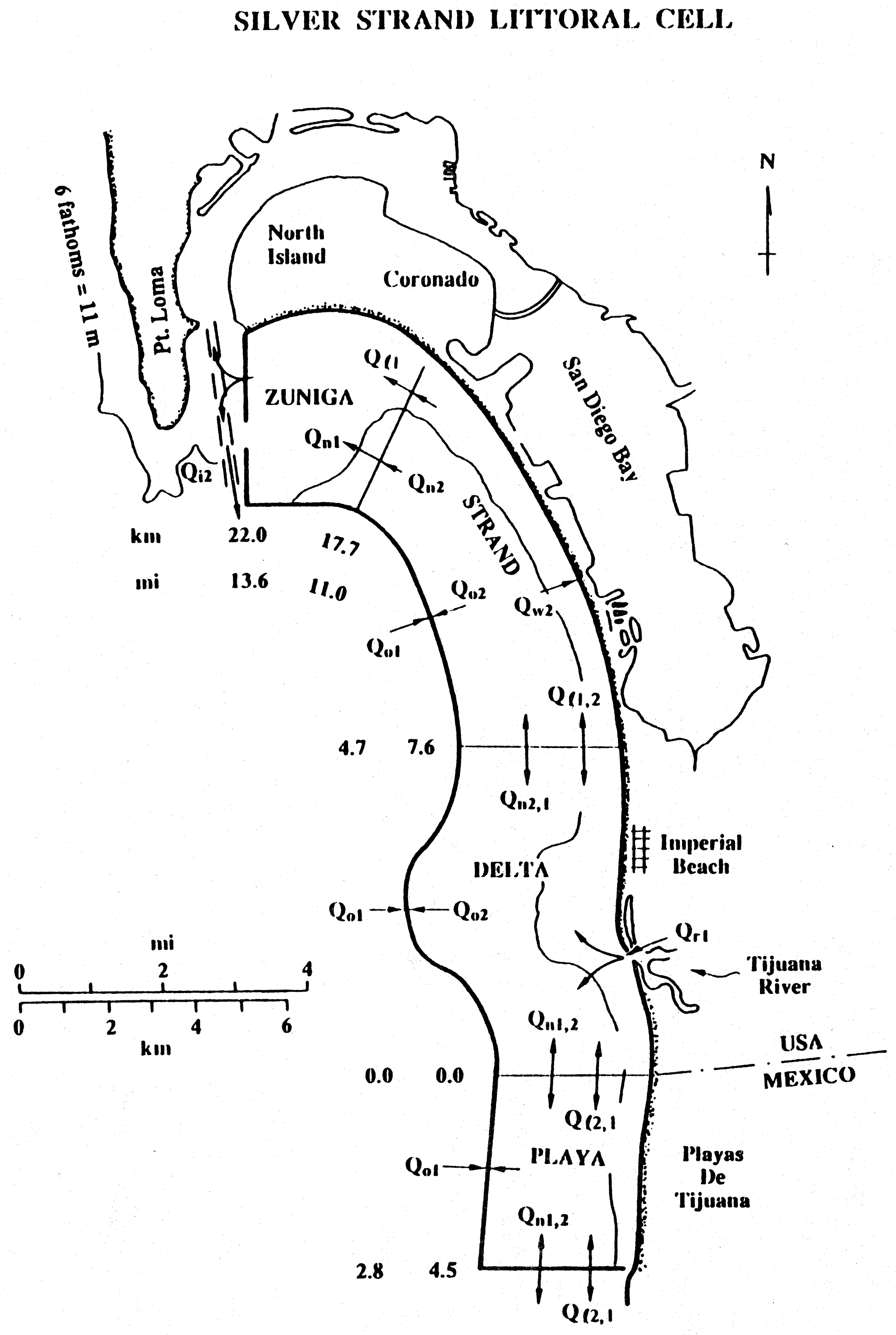


Figure 9-19. Elements of the sediment budget for Silver Strand Littoral Cell and its four subcells. Symbols are defined in Table 9-11.

tombolo to the north. The development of the tombolo and the formation of San Diego Bay as a result of wave action and sealevel rise during the early Holocene have been discussed in Masters (1988). Under natural conditions, Zuñiga Shoals at the entrance to San Diego Bay was created by northerly transport which has continued to supply the Silver Strand beaches with sand. Formerly, sand from Zuñiga shoals was naturally recycled south to Coronado and Silver Strand beaches.

Human intervention has drastically altered natural processes within the Silver Strand Littoral Cell. Construction of Zuñiga Jetty from 1893 to 1904 strengthened and extended the ebb-tide jet from the bay, causing the tidal delta to move into deeper water, and creating an artificial sink for sediment (Inman et al., 1974; Inman, 1976). Recirculation of sand from Zuñiga Shoals can no longer occur to replenish the beaches to the east and south. In addition a hooked groin was built for the Hotel Del Coronado in 1897 and extended in 1900. As a result of these structures, severe erosion occurred along the Coronado beaches, and the Coronado Seawall was constructed in 1906-07.

Construction of Rodriguez Dam in Mexico and Morena and Barrett Dams in the United States has eliminated the Tijuana River as a significant source of sediment for the cell. This has caused serious erosion in the vicinity of Imperial Beach and into Mexico.

Massive harbor construction activities within San Diego Bay following World War II generated vast quantities of "new source" sand to nourish the beaches of the Silver Strand. This type of human intervention has slowed the effects of the erosion waves generated by loss of material from the Tijuana River.

9.8.1 Analysis of Budget of Sediment

The analysis is carried out within four subcells, three within the United States and one in Mexico (Figure 9-19). This division generally follows that used by Everts (1987: CCSTWS 87-3). The principal difference between the present analysis and that by Everts (ibid.) is that Everts did not recognize the loss of sediment through the Zuñiga jetties. The semi-permeable jetties permit sand to filter through and into the bay's entrance channel where it is jetted out and deposited in depths of 18 to 30 m (60-100 ft).

Details of beach changes and cliff erosion within the Playas subcell (Figure 9-19) have been worked out by Everts (1987: CCSTWS 87-3). This subcell formerly was characterized by a sandy beach backed by seacliffs. Recently, it has experienced extensive erosion and loss of property.

The Delta subcell has a seaward, submarine protrusion persisting from the Pleistocene delta of the Tijuana River. Wave refraction over this feature has been important to the formation of the Silver Strand Littoral Cell. High waves drove sand both north and south from the deposits of the delta. Immediately after damming of the Tijuana River, the delta provided the major source of sand for the cell. Therefore, $Q_{o\ell}$ (onshore transport by waves) was a significant input to the system. However, waves have winnowed sand out of the submerged delta deposits, leaving only boulders, and the delta can no longer supply sand to the transport regime. The erosion south of Imperial Beach began in 1937 immediately after completion of Rodriguez Dam on the Tijuana River. Intermittent supply of sand from the delta has not been sufficient in recent years to control erosion of these beaches. The two rock groins constructed in 1959 and 1961 have not proven effective in preventing beach erosion.

The Strand subcell is a 10 km (6 mi) long sand spit extending from the south end of the bay to the Hotel del Coronado. This subcell has undergone the largest changes in terms of erosion and artificial filling. Due to erosion waves moving north through the cell, the Strand shoreline continues to erode. Between 1941 and 1985, approximately 24 x 10^6 m^3 (31 x 10^6 yd^3) of sand dredged from San Diego Bay was placed on the central Silver Strand (California, 1980). This material advanced the shoreline seaward in the fill area over 300 m (985 ft). However, since 1946 the shoreline has steadily retreated as the sand has been transported north through the cell.

The Zuñiga subcell is now a sand storage area. However, erosion was first observed on Coronado Beach in 1905 shortly after construction of Zuñiga jetty and the extension of the hooked groin at Hotel Del Coronado in 1900. The permeable jetty caused strong tidal ebb currents to aspirate sand through the jetty to the east, while the groin initially prevented sand from traveling northeast into the area. In response to continuing erosion, a revetment wall was constructed in 1906-1907 along Ocean Avenue in Coronado. The Zuñiga subcell was filled with sand in the first major beach nourishment project on the Silver Strand in 1940/41 (Table 9-20). The sand nourishment supplemented by sand transported around the Hotel Del Coronado groin has filled the subcell, and it is now a major sand deposit.

In the three budget estimates that follow (Tables 9-18, 9-19, and 9-21), the guiding consideration for estimating the longshore transports away from the submerged delta of the Tijuana River is the river input, which under natural conditions provided a more or less stable shoreline. With this in mind, we then apply assumptions (1) through (5) as listed in Section 9.6.1.

Natural, Pre-Dam Conditions circa 1905-1936

There are very little quantitative data on longshore transport rates, primarily because the area is open to the south through southwest to west, and we have no reliable wave statistics for southerly waves. Further, refraction over the submerged delta of the Tijuana River (Figure 9-19) makes interpretation of wave arrays difficult.

However it should be noted that wave convergence over the delta will increase longshore transport away from the delta in both directions by creating stronger longshore currents and by producing a gradient in breaker height. The general relations leading to increased longshore transport are discussed in Chapter 5.3.3, and the specific types of longshore currents along the Delta subcell in Inman, et al. (1971). In any event, over time, longshore transport out of this subcell, combining Q_ℓ and Q_n, was equal to the river input, here estimated for pre-dam conditions to be Q_r = 200,000 m^3/yr (260,000 yd^3/yr) (see Table 9-7).

The budget shown in Table 9-18 assumes that the longshore transport out of the Delta subcell is equal to the river input for natural conditions, and that three-quarters of this amount under natural conditions was transported to the north and one-quarter to the south into Mexico. The other major assumption here is that, at least early in the period, following construction of Zuñiga Jetty in 1904, the increased ebb-tide jet current through the entrance channel aspirated material through the porous jetty and deposited it in deeper water (see Inman, et al., 1974; Inman, 1975). This effect is listed under Q_i for the Zuñiga subcell.

This time period was one in which the littoral cell, except for the Zuñiga subcell, was essentially in equilibrium. Therefore, this period is used as a calibration for the budgets that follow.

Uniform Northwesterly Wave Climate circa 1950-1978

The dominant change during this period was the damming of the Tijuana River and the dramatic decrease to about one-quarter of its natural yield. Compare the river yield in Table 9-7 with the entries under Q_r in Table 9-19 and its value in the previous budget. Fortunately, the decrease in river yield was more than offset by a massive placement of "new source" nourishment in the Strand subcell. Refer to Table 9-20 and the entry for Q_a in Table 9-19.

The erosion of the delta continued and its erosion wave moved north into the Strand subcell where it was neutralized by nourishment. Note that it is now assumed that the build up of Zuñiga Shoals east of the jetty has produced a blocking action that

TABLE 9-18
SILVER STRAND LITTORAL CELL
NATURAL, PRE-DAM CONDITIONS CIRCA 1905-1936
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcells							
	Zuñiga ℓ = 4.3 km		Strand ℓ = 10.1 km		Delta ℓ = 7.6 km		Playa ℓ = 4.5 km	
	Input	Output	Input	Output	Input	Output	Input	Output
$Q_{\ell n}$[a] (north)	130	0	150	130	0	150	0	0
$Q_{\ell,n}$[a] (south)	0	0	0	0	0	50	50	50
Q_o[b]	0	0	0	0	0	0	0	0
Q_a[c]	0	0	0	0	0	0	0	0
$Q_{r,i}$[d]	0	750	0	0	200	0	0	0
$Q_{b,w}$[e]	0	0	0	20	0	0	0	0
Total	130	-750	150	-150	200	-200	50	50
Net ($\partial V'/\partial t$)[f]	-620		0		0		0	
$\partial X/\partial t$ (m/yr)[g]			0		0		0	
	erosion		balance		balance		balance	

[a] Sum of Q_ℓ and Q_n assumed to equal Q_r with 3/4 transported north and 1/4 to the south.

[b] and [c] Onshore transport $Q_{o\ell}$ and downwelling Q_{02} assumed to be in equilibrium; there was no artificial nourishment Q_a.

[d] River yield $Q_{r\ell}$ average "natural" of 200 x 10^3 m^3/yr (Table 9-7). Sand loss Q_{i2} from Zuñiga Shoal assumed ½ rate of 1,500 x 10^3 m^3/—yr determined from bathymetric surveys of 1923-1934 (Chamberlain, et al., 1958; refer to text).

[e] Wind and overwash Q_{w2} = 2 m^3/—yr; assumed 2/5 rate measured at Pismo Beach, California (Bowen & Inman, 1966). Bluffland and cliff erosion $Q_{b\ell}$ assumed zero.

[f] Except for the known erosion in Zuñiga subcell due to jetties and groin construction, the other subcells were required to balance for this "natural" calibration period.

[g] From equations 9-2 and 9-3, for Z = 14 m. This relation does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

TABLE 9-19
SILVER STRAND LITTORAL CELL
UNIFORM NW WAVE CLIMATE CIRCA 1950-1978
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcells							
	Zuñiga ℓ = 4.3 km		Strand ℓ = 10.1 km		Delta ℓ = 7.6 km		Playa ℓ = 4.5 km	
	Input	Output	Input	Output	Input	Output	Input	Output
$Q_{\ell n}$[a] (north)	130	0	50	130	0	50	0	0
$Q_{\ell,n}$[a] (south)	0	0	0	0	0	150	150	150
Q_o[b]	0	0	0	0	100	0	0	0
Q_a[c]	0	0	630	0	0	0	0	0
$Q_{r,i}$[d]	0	130	0	0	50	0	0	0
$Q_{b,w}$[e]	0	0	0	20	0	0	0	0
Total	130	-130	680	-150	150	-200	150	-150
Net $(\partial V'/\partial t)$[f]	0		+530		-50		0	
$\partial X/\partial t$ (m/yr)[g]			3.75		0.47		0	
	balance		accretion		erosion		balance	

[a] Uniform weather with waves from northwest induces southerly transport from Delta subcell south; Point Loma wave shelter permits northerly transport from Strand to Zuñiga subcell.

[b] Decreased river discharge causes beach recession and a wave-induced onshore transport of sand from submerged delta.

[c] Artificial nourishment $Q_{a\ell}$ from Table 9-20.

[d] River yield $Q_{r\ell}$ for present conditions, Table 9-7.

[e] Wind and overwash Q_{w2} = 2 m^3/—yr; assumed 2/5 rate measured at Pismo Beach, California (Bowen & Inman, 1966). Bluffland and cliff erosion $Q_{b\ell}$ assumed zero.

[f] Artificial nourishment resulted in widening of Strand beaches.

[g] From equations 9-2 and 9-3, for Z = 14 m. This relation does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

TABLE 9-20
SILVER STRAND LITTORAL CELL
BEACH NOURISHMENT

		Reach[a]		Quantity	
Year	Subcell	km	mi	m^3	yd^3
1941	Zuñiga	20-22	12.6-13.6	1,730,000	2,260,000
1946	Strand	14-17	8.8-10.8	20,050,000	26,200,000
1967	Strand	16	10	30,000	40,000
1976	Strand	14-17	8.8-10.8	2,680,000	3,500,000
1977	Delta	4-5.5	2.5-3.5	840,000	1,100,000
1985	Strand	15-16.5	9.5-10.2	840,000	1,100,000
Total 1941-1985				26,200,000	34,200,000
Total Strand + Delta Subcells				24,470,000	31,740,000
Rate 1946-1985 (volume/yr)				627,000	814,000

[a] Reach of beach nourishment in km (mi) north of the U. S./Mexico border (Figure 9-19).

Source: Everts (1987: CCSTWS 87-3, Table 4) decreases the sand lost by aspiration through the jetty. Thus for this period, the Delta subcell was the only one showing significant erosion, and some of that is counteracted by onshore transport $Q_{o\ell}$ of sand from the submerged delta.

Variable Westerly Wave Climate circa 1983-1990

This period of variable weather was preceded by the cluster storms of 1982/83. Comparisons of the National Ocean Survey bathymetry of 1934 and 1968 indicate erosion of the Delta Subcell and deposition in the northern part of the Strand subcell (see Everts, 1987: CCSTWS 87-3, Figure 32). Some of this transfer was undoubtedly due to a northwest transport along the shelf by the tropical storm of September 1939. However, erosion of the delta was likely associated with the loss of the river source as described in the previous budget.

The budget for this period, as shown in Table 9-21, is characterized by erosion. The erosion wave that began at the delta with the decrease in river yield has now traveled both north and south of the delta. The erosion in the Strand subcell would have been much worse except for the immense amount of "new source" nourishment, some of which persisted into this period. The shoreline changes $\partial X/\partial t$ shown in Table 9-21 should be compared with Table 9-20 and Figure 9-20.

9.8.2 Predictions for the Future

Budget estimates for the three time periods are, at best, guides to the real fluctuations in the Silver Strand Littoral Cell. The phenomenological budgets in Tables 9-18, 9-19, and 9-21 are in fair agreement with the time history of sediment volume changes calculated by Everts (1987: CCSTWS 87-3) and based on shoreline changes (Figure 9-20). The agreement lends support to the budget analyses presented here.

In general, the Silver Strand Littoral Cell is undergoing erosion now, despite the massive injections of "new source" nourishment. It is essential that sources of potential nourishment be located and means of dispensing nourishment to the beaches be perfected. The minimum long-term rate of new source material is estimated to be that of the previous yield of the Tijuana River, say about 200,000 m^3/yr (260,000 yd^3/yr). However, considering the anticipated rise in sealevel, a rate several times this amount may be required, perhaps up to 600,000 m^3/yr (800,000 yd^3/yr).

TABLE 9-21
SILVER STRAND LITTORAL CELL
VARIABLE W WAVE CLIMATE CIRCA 1983-1990
SEDIMENT BUDGET IN 10^3 m^3/yr

	Subcells							
	Zuñiga ℓ = 4.3 km		Strand ℓ = 10.1 km		Delta ℓ = 7.6 km		Playa ℓ = 4.5 km	
	Input	Output	Input	Output	Input	Output	Input	Output
$Q_{\ell n}$[a] (north)	130	0	50	130	0	50	0	0
$Q_{\ell,n}$[a] (south)	0	0	0	0	0	50	50	75
Q_o[b]	0	0	50	0	0	0	0	0
Q_a[c]	0	0	20	0	0	0	0	0
$Q_{r,i}$[d]	0	130	0	0	50	0	0	0
$Q_{b,w}$[e]	0	0	0	20	0	0	10	0
Total	130	-130	120	-150	50	-100	60	-75
Net ($\partial V'/\partial t$)[f]	0		-30		-50		-15	
$\partial X/\partial t$ (m/yr)[g]			0.21		0.47		0.24	
	balance		erosion		erosion		erosion	

[a] Variable weather with prevailing waves from west decreases southerly transport from Delta and Playa subcells; Point Loma wave shelter permits northerly transport from Strand to Zuñiga subcell.

[b] Previous budget depleted offshore source (only cobbles remain on submerged delta), $Q_{o\ell}$ (Delta) now zero, but some shelf source for Strand subcell.

[c] Artificial nourishment ceases in 1985; some remainder from 1985 nourishment (Table 9-20).

[d] River yield $Q_{r\ell}$ for present conditions, Table 9-7.

[e] Wind and overwash Q_{w2} = 2 m^3/—yr; assumed 2/5 rate measured at Pismo Beach, California (Bowen & Inman, 1966). Bluffland and cliff erosion $Q_{b\ell}$ assumed zero, except for the Playa where it is estimated to be 10 x 10^3 m^3/yr.

[f] From equations 9-2 and 9-3, for Z = 14 m. This relation does not include the estimated 9 cm/yr shoreline recession associated with sealevel rise.

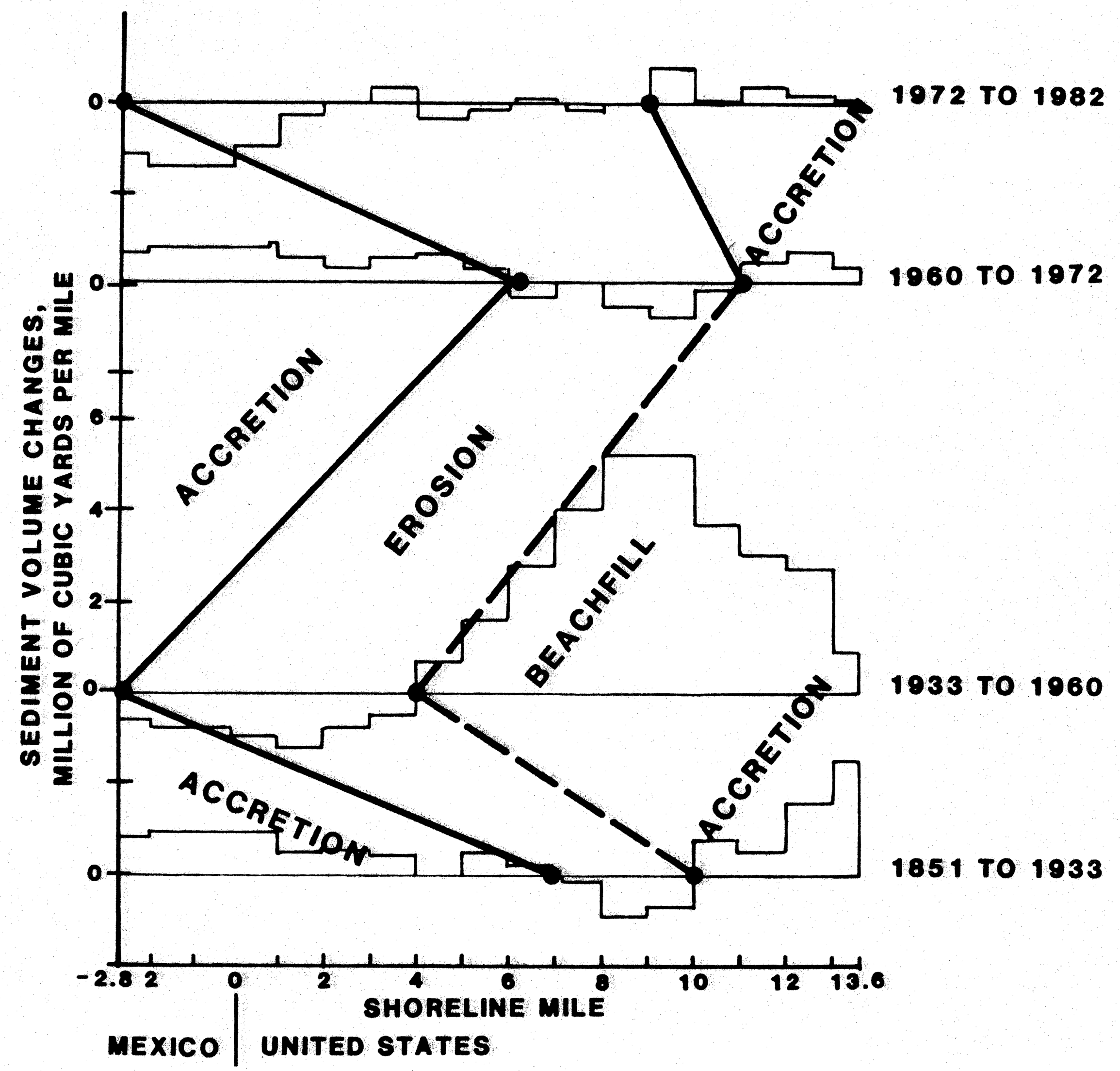


Figure 9-20. Sediment volume changes for Silver Strand Littoral Cell 1851-1982 (from Everts, 1987: CCSTWS 87-3). Sediment volume estimated from a relation similar to equation 9-2 with z ranging from 6.7 m (22 ft) at Zuniga Shoals to 16.8 m (55 ft) at Kilometer 8 (Mile 5).

9.9 SUMMARY AND PREDICTIONS

9.9.1 General Observations

The present study considers the different types of sediment response to a wide range of forcing by waves and currents within the three littoral cells of the San Diego Region. This procedure provides the basis for preparing plans for future contingencies, even though we cannot predict the future with any degree of certainty. Generally, our beaches appear to be in reasonably good condition. However, this status prevails only because of seven years of "fair" weather since the cluster storms of 1982/83 and because there have been massive injections of "new source" sand nourishment in all three littoral cells.

The historic past shows that the quantity of sand on the beaches has varied widely. These fluctuations are related to sand supply, downcoast propagation of accretion and erosion waves, occurrence of high total-energy storms and cluster storms, and in recent years, progressively greater repercussions of human intervention.

A number of new insights regarding the mechanisms of sediment transport and the significant variables in the budget of sediment have emerged from the CCSTWS studies. We have used these advances in our analyses of the three littoral cells of the San Diego Region. The budgets of sediment for the three cells for various wave climates are summarized in Figures 9-21 through 9-23, where the budget is presented in both metric (a) and U.S. conventional (b) units. The contributions to our understanding of littoral processes in the San Diego Region can be summarized as follows:

(1) Significant new inputs to the budget are the yields from coastal blufflands and, where the slopes are gentle, the nearshore shelf.

(2) Cluster storms and high total-energy storms appear to drive downwelling currents that carry sand onto the shelves of the San Diego Region. Along the steeply sloping shelf of the Oceanside Littoral Cell, the sand is permanently lost from the shorezone.

(3) Historical profiles show changes to their maximum measured depth of about 40 ft MLLW and correlate with the occurrence of cluster storms and high total-energy storms.

(4) These profile changes demonstrate the transport mechanism operating between sediment stored in the shorezone and sediment downwelled onto the shelf.

A number of principles about the retention of sand on beaches and the mechanisms of recuperation following severe storms are highlighted by this study. Normal wave action contains sand against the coast and, when sediment sources are available, results in accretion of the shorezone. High total-energy wave events cause a loss of sand from the shorezone via downwelling currents that deposit sand on the shelf. These accretion and erosion cycles are analogous to a slowly filling reservoir, followed by a sudden loss of sand and water when the sluice gates are opened. The downwelled sediment is lost to the shorezone when deposited on a steep shelf such as that of the Oceanside Cell, or it may be returned gradually from a gently sloping shelf to the shorezone by wave action. Downwelled sand is probably returned to the beaches of the Mission Bay and Silver Strand Littoral Cells.

In all cases where measurements were made just before and after the 1982/83 cluster storm events, and the profiles were distant from structures, it was found that these events resulted in the lowest level of beach sand in the history of the observations. Using the profiles north of Oceanside Harbor where conditions are closest to natural and unaffected by harbor effects, it is found that the 38 km (24 mi) of the central Oceanside subcell during 1982/83 lost an unprecedented 33 million cubic meters (43 million yd^3) of sand from the shorezone in one year! Such a volume represents perhaps a 50-year supply of sediment to the shorezone under normal conditions.

Cluster storm events can cause permanent profile changes to depths of 40 feet and deeper. During mild years, the beaches recover in their bar-berm sections but not necessarily in the deeper shorerise portion. Thus the health of the beach is closely associated with the occurrence of these episodic events, and the time elapsed since the events.

There are two scenarios with regard to the future health of the beaches:

(1) For as long as relatively mild wave climate persists, the beaches will remain in their present state.

(2) The next season of high total-energy storms will lead to extensive erosion that may be as bad as, or worse than, that following the cluster storms of 1982/83.

During the next 50 years, the most significant, and still unpredictable, set of variables are the coastal wave climate and its episodic changes. The second significant and unquantified variable is the rate of sealevel rise. Given that the San Diego Region is on a collision coast with sandy beaches backed by seacliffs, beach erosion and failure of the seacliffs must be anticipated. Extensive damage and loss of property will occur. The magnitude of the erosion will depend on both the wave climate and sealevel change.

Preventive intervention will require the identification and mobilization of new sources of sand to nourish the most depleted beaches. Monitoring of the beach profiles should continue on a regular schedule in order to expedite nourishment responses.

Natural sources of beach sand have been the rivers, streams, and lagoons of the San Diego Region. Dams have reduced the yield of rivers and streams almost to negligible quantities. Urbanization, however, has accelerated the erosion of coastal blufflands and sedimentation of lagoons (State Coastal Conservancy, 1989). The alluvia in lagoons and river channels still represent potential sediment sources that can be mined where land uses have not precluded this possibility. Table 9-3 lists localities having more than 30 million yd^3 of available sand. Agua Hedionda Lagoon has already contributed sufficient sand to generate an accretion wave that ended the severe erosion in the southern section of the Oceanside Littoral Cell. Dredging of San Diego Bay has fed more than 26×10^6 m^3 ($>34 \times 10^6$ yd^3) into the Silver Strand Littoral Cell. Municipalities and regional governments should be making land use decisions with the goal of reserving these sand sources for present and future needs. There also may have to be environmental trade-offs in terms of wetland habitats within the lagoons versus healthy beaches.

New sources of sand may require creative solutions: mining from Zuñiga Shoals, recovery and recycling from the heads of submarine canyons, or releasing from dam entrapment (e.g., Inman & Harris, 1970; Wasyl, et al., 1991). Efforts to develop the necessary new technologies are long overdue and should be initiated immediately.

In the long term, decisions will have to be made to let the seacliffs erode. Zoning codes should be modified, and the sooner such decisions are made, the lower the economic impact will be. A philosophy of "damage control" would be more appropriate than "save the cliffs at all costs." In the long term, rational policy permitting sea cliff retreat may be less costly than total fortification.

In summary, all the beaches of the San Diego Region are threatened with erosion. The apparent stability of the beaches is belied by rigorous examination of the historical beach profiles and summation of previous beach nourishment. Without the earlier massive inputs of beachfill, the shoreline of the San Diego Region would exhibit nearly continuous erosion from Dana Point to the international border. New sources of beach-quality sand need to be readied for beach nourishment following severe storm events and for long-term protection from rising sealevel. Just as water districts provide reservoirs as a margin of safety during prolonged droughts, sand management districts should plan for future needs of beach nourishment.

Sand Management: Needed Studies

It is apparent that future health of beaches will be critically dependent upon adequate sources of sand. Therefore it is imperative that studies be undertaken to determine: (1) the possible sources, (2) the mechanics and economics of transport and dispersal, (3) the best means of keeping sand on the beach, and (4) the possibility of minimizing loss into sinks.

Wave Climate and Implications for Coastal Engineering

Comparisons of the effects of the most intense storm of the century in January 1988 with that of the storm clusters of 1982/83 illustrate fundamental concepts of the application of wave data to coastal engineering. The maximum value of the wave intensity or energy (e.g., joules) applies to all impulse-response phenomena such as runup, overtopping and stability of structures (see Inman & Jenkins, 1989). Thus a measure of the highest waves is an important criterion leading to the "design wave". The highest wave concept is also important in terms of breaking ledges in submarine canyons and destroying kelp beds as demonstrated by the January 1988 storm (Seymour, 1989; Dayton, et al., 1989).

On the other hand, sand transport rate is proportional to the energy flux (joules/sec = watts) of the waves, while the total amount of sediment transported is proportional to the total energy (watt-hours). Thus a long duration but low intensity storm may have more effect on the crosshore and longshore transport of sand and the form of beach profiles than a short duration, high intensity storm (e.g., Dolan, et al., 1990).

Similarly, tsunamis with their high nearshore waves may be the most destructive wave phenomena to coastal structures and reefs, but they may not seriously affect the budget of littoral sand. These considerations explain why the effects of the January 1988 storm were restricted to the bar-berm portions of the beach profile and the beaches totally recovered in a few months (refer to Figure 9-11). In contrast, the cluster storm events of 1982/83 caused erosion of the shorerise portion of the beach profiles in depths of 18 m (60 ft) which had not recovered by 1987, the date of the last survey that extended to these depths (refer to Figure 9-10).

In terms of assessing real changes in wave climate versus normal cycles of mild and severe weather (Section 9.3), the database now available includes information from deep-water sensors which may be biasing our analyses. Is the increase in high waves simply due to the gauge at Begg Rock? Is it possible that the high waves measured from that station since 1982 have always been out there, but island sheltering had decreased the coastal effect to mere noise?

Wave Climate: Needed Studies

Wave climate information has been inadequate and the advantages and disadvantages of deep-water wave sensors versus coastal arrays should be carefully studied. New techniques of refraction-diffraction analysis have vastly extended our ability to interpret deep-water wave data. Locations of deep-water sensors should be selected on the basis of refraction-diffraction analyses.

Beach Profiles: Needed Studies

This study shows that the traditional profile carried to depths of 10 m (30 ft) covers only seasonal changes and does not include the effects of high total-energy events. It is necessary that profiles be extended to depths of 15 to 18 m (50 to 60 ft) and that these be measured routinely at least twice a year (fall and spring). In addition, they should be measured immediately following episodic high total-energy events.

Profiles should be spaced at least every 1.5 km (1 mi) along all sandy portions of the coast. The present study was considerably hindered by absence of historic profiles north of Oceanside Harbor, and in the northern portions of Mission Beach and Silver Strand. There are usually sufficient profiles near structures, but these profiles tell little about conditions away from the structures.

9.9.2 Oceanside Littoral Cell

Beach and coastal conditions in the Oceanside cell can be expected to follow patterns of erosion and accretion similar to the past 50 years, but with accelerated trends towards erosion because of (1) loss of stream supply behind dams, (2) erosion in downcoast reaches of Oceanside Harbor, and (3) increase in the rate of sealevel rise. A summary of the sediment budgets for periods of uniform wave climate is given in Figure 9-21. It should be noted that these uniform periods are terminated by erosional events such as the 1982/83 cluster storms.

In the past this coast has always had periods of relatively abundant sand supply following large sand injections by river floods. Downcoast traveling accretion waves have acted to naturally nourish the beaches. Following high total-energy storm events, the beaches are denuded by downwelling of sand onto the steep shelf, where it is mostly lost to the shorezone. These episodic events are followed by erosion sequences. Human intervention in the form of Oceanside Harbor and dams on streams has had significant impacts that balance the scale towards erosion. This trend has been counteracted in the past by large quantities of artificial nourishment (e.g., dredging of Oceanside Harbor basin,

Input or Output		Natural Conditions ca.1900-1938 Input	Natural Conditions ca.1900-1938 Output	Uniform NW Wave Climate ca.1960-1978 Input	Uniform NW Wave Climate ca.1960-1978 Output	Variable W Wave Climate ca.1983-1990 Input	Variable W Wave Climate ca.1983-1990 Output
Q_l+Q_n	Longshore	0	145	0	145	0	40
Q_r	River	65	0	45	0	45	0
Q_b, Q_o	Bluff, Offshore	130	45	90	45	0	0
Q_a	Nourish	0	0	90	0	0	0
$\partial V'/\partial t$ (10^3 m^3/yr)		**+5**		**+35**		**+5**	
$\partial X/\partial t$ (cm/yr)		**≈ balance**		**18 accretion**		**≈ balance**	
Q_l+Q_n		145	210	145	210	40	55
Q_r		210	0	20	0	0	0
Q_b, Q_o		400	490	280	350	140	0
Q_a		0	0	50	0	25	0
$\partial V'/\partial t$ (10^3 m^3/yr)				**-65**		**+150**	
$\partial X/\partial t$ (cm/yr)				**7 erosion**		**40 accretion**	
HARBOR EFFECTS							
$Q_{ld}+Q_{nd}$	Deflection			0	60	0	15
Q_l+Q_n				210	210	55	55
Q_r				30	0	0	0
Q_b, Q_o				120	140	60	0
Q_a				75	0	0	0
$\partial V'/\partial t$ (10^3 m^3/yr)		**+55**		**+25**		**+45**	
$\partial X/\partial t$ (cm/yr)		**10 accretion**		**16 accretion**		**29 accretion**	
Q_l+Q_n		210	0	210	0	55	0
Q_r		50	0	5	0	0	0
Q_b, Q_o		150	180	150	180	75	0
Q_a, Q_s	Nour., Sub Canyon	0	220	75	220	0	55
$\partial V'/\partial t$ (10^3 m^3/yr)		**+10**		**+40**		**+75**	
$\partial X/\partial t$ (cm/yr)		**≈ balance**		**9 accretion**		**17 accretion**	

Episodic Beach Denudation: **1939 Tropical Storm** | **1982/83 Cluster Storms**

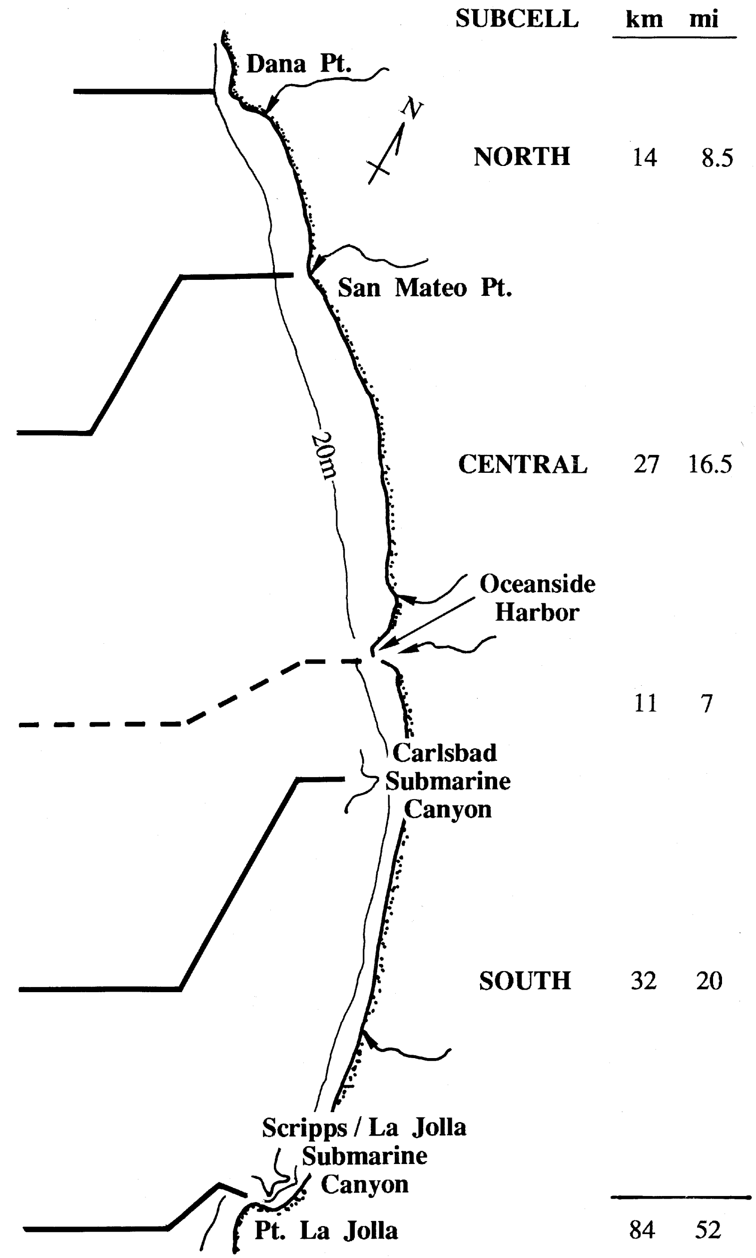
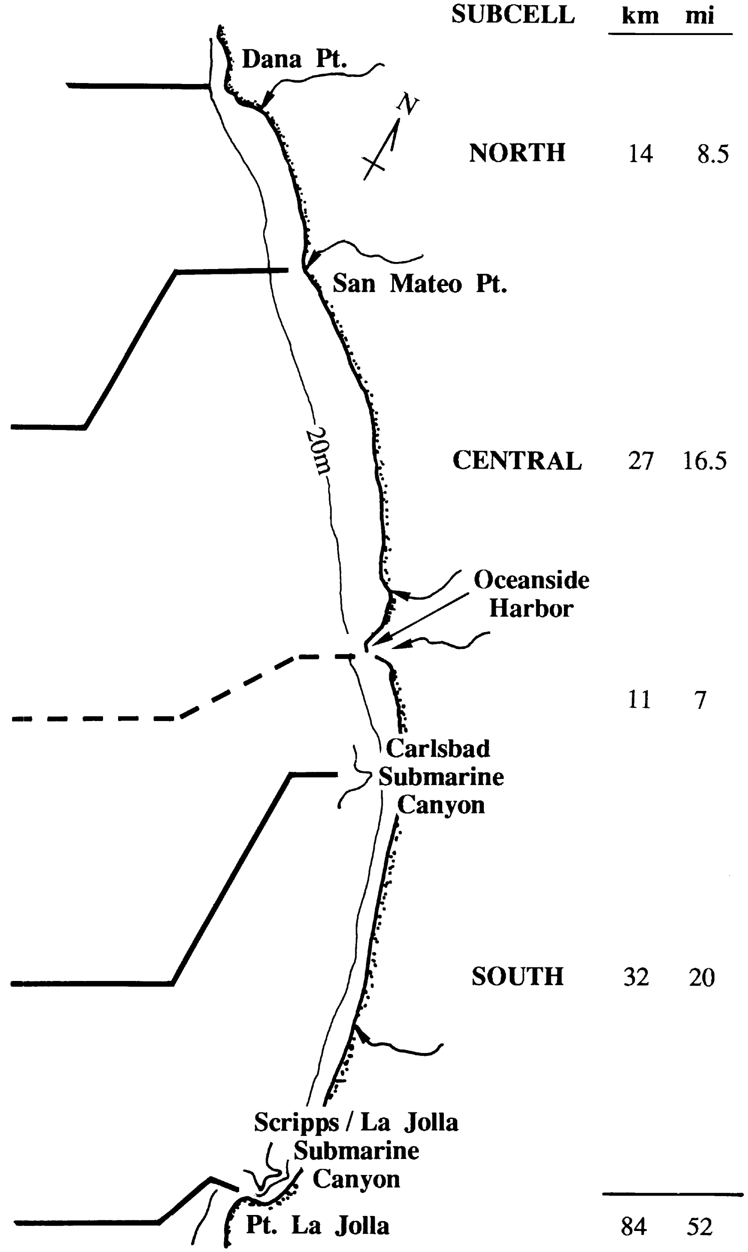


Figure 9-21. (a) Summary of the Budgets of Sediment for Oceanside Littoral Cell in 10^3 m^3/yr.

91.119-21a

Input or Output		Natural Conditions ca.1900-1938 Input	Natural Conditions ca.1900-1938 Output	Uniform NW Wave Climate ca.1960-1978 Input	Uniform NW Wave Climate ca.1960-1978 Output	Variable W Wave Climate ca.1983-1990 Input	Variable W Wave Climate ca.1983-1990 Output
Q_l+Q_n	Longshore	0	190	0	190	0	50
Q_r	River	85	0	60	0	60	0
Q_b, Q_o	Bluff,Offshore	170	60	120	60	0	0
Q_a	Nourish	0	0	120	0	0	0
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+5**		**+50**		**+10**	
$\partial X/\partial t$ (ft/yr)		**≈ balance**		**0.7 accretion**		**≈ balance**	
Q_l+Q_n		190	270	190	270	60	70
Q_r		270	0	25	0	0	0
Q_b, Q_o		520	640	370	460	180	0
Q_a		0	0	65	0	30	0
$\partial V'/\partial t$ (10^3 yd^3/yr)				**-80**		**+200**	
$\partial X/\partial t$ (ft/yr)				**0.6 erosion**		**1.4 accretion**	
HARBOR EFFECTS							
$Q_{ld}+Q_{nd}$	Deflection			0	80	0	20
Q_l+Q_n				270	270	70	70
Q_r				40	0	0	0
Q_b, Q_o				160	180	80	0
Q_a				100	0	0	0
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+70**		**+40**		**+60**	
$\partial X/\partial t$ (ft/yr)		**0.3 accretion**		**0.7 accretion**		**1.0 accretion**	
Q_l+Q_n		270	0	270	0	70	0
Q_r		65	0	5	0	0	0
Q_b, Q_o		200	240	200	240	100	0
Q_a, Q_s	Nour.,Sub Canyon	0	290	100	290	0	70
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+5**		**+45**		**+100**	
$\partial X/\partial t$ (ft/yr)		**≈ balance**		**0.3 accretion**		**0.6 accretion**	



Episodic Beach Denudation: **1939 Tropical Storm** **1982/83 Cluster Storms**

Figure 9-21. (b) Summary of the Budgets of Sediment for Oceanside Littoral Cell in 10^3 yd^3/yr.

91.119-21b

Agua Hedionda Lagoon, and excavation of the cliffs at the San Onofre Power Plant).

The most critical coastal reaches in the future are those south of Oceanside Harbor, where urbanization and construction of cliff-edge residences have been extensive. These areas will continue to erode and, in terms of decades to 50 years, erosion probably will accelerate. It should be emphasized that the most effective erosion control device is a wide beach.

A second area of concern is San Clemente, which exists as a beach community only because of past major artificial nourishment. Budget details and the amounts of material involved are summarized in Figure 9-21. These budgets are for various wave climates, and serve as the basis for the necessary ongoing study and planning required to maintain beaches in this area.

Specific Studies

(1) Effect of Oceanside Harbor on downcoast beaches. This should be a detailed study based on increased number and repeated profiles run to depths of 15 m (50 ft) generally and to 18 m (60 ft) in the vicinity of the harbor. The study should include better daily wave data. In addition, sand tracer studies are needed to identify paths and quantities of transport.

(2) Study of loss in Carlsbad and Scripps Submarine Canyons, with objective of limiting loss down the canyons.

(3) More extensive, better controlled studies and monitoring of blufflands erosion and its contribution to the beaches.

9.9.3 Mission Bay Littoral Cell

This littoral cell will remain reasonably stable during periods of mild wave climate. However its only significant source of beach sand has been the San Diego River which is now reduced to about one-quarter or less of its former yield. This decline has caused increased cliff and bluffland erosion to supplement the loss from rivers. In the long term, this cell probably will require about 100,000 m^3/yr (130,000 yd^3/yr) of "new source" beach nourishment. Budget details and amounts of material involved are summarized in Figure 9-22. These budgets serve as a beginning for the necessary ongoing study and planning required to maintain the shorelines of Mission Beach and Ocean Beach.

Specific Studies

(1) It is important to find "new sources" of sand and the means of bringing sand to the beach.

Input or Output		Uniform NW Wave Climate ca.1960-1978 Input	Uniform NW Wave Climate ca.1960-1978 Output	Variable W Wave Climate ca.1983-1990 Input	Variable W Wave Climate ca.1983-1990 Output	SUBCELL	km	mi
Q_n	Longshore	0	5	0	0	PT. LA JOLLA	5.8	3.6
Q_r, Q_s	River, Canyon	0	5	0	10			
Q_b, Q_o	Bluff, Offshore	10	0	10	0			
Q_a	Nourish	0	0	0	0			
$\partial V'/\partial t$ (10^3 m^3/yr)		**0 balance**		**0 balance**				
Q_n		5	5	0	0	MISSION BEACH	5.8	3.6
Q_r, Q_i	River, Inlet	5	5	5	5			
Q_b, Q_o		0	0	0	0			
Q_a		25	10	5	10			
$\partial V'/\partial t$ (10^3 m^3/yr) $\partial X/\partial t$ (cm/yr)		**+15 18 accretion**		**-5 6 erosion**				
Q_n		5	10	0	0	OCEAN BEACH	1.2	0.8
$Q_r + Q_i$		10	5	10	5			
$Q_b + Q_o$		0	0	0	0			
Q_a		10	5	0	5			
$\partial V'/\partial t$ (10^3 m^3/yr) $\partial X/\partial t$ (cm/yr)		**+5 30 accretion**		**0 balance**				
Q_n		10	10	0	0	PT. LOMA	9.7	6.0
Q_r		0	0	0	0			
Q_b, Q_o		20	10	20	10			
Q_a		0	0	0	0			
$\partial V'/\partial t$ (10^3 m^3/yr) Offshore		**+10 accretion**		**+10 accretion**				
							22.5	14.0

Episodic Beach Erosion: **1982/83 Cluster Storms**

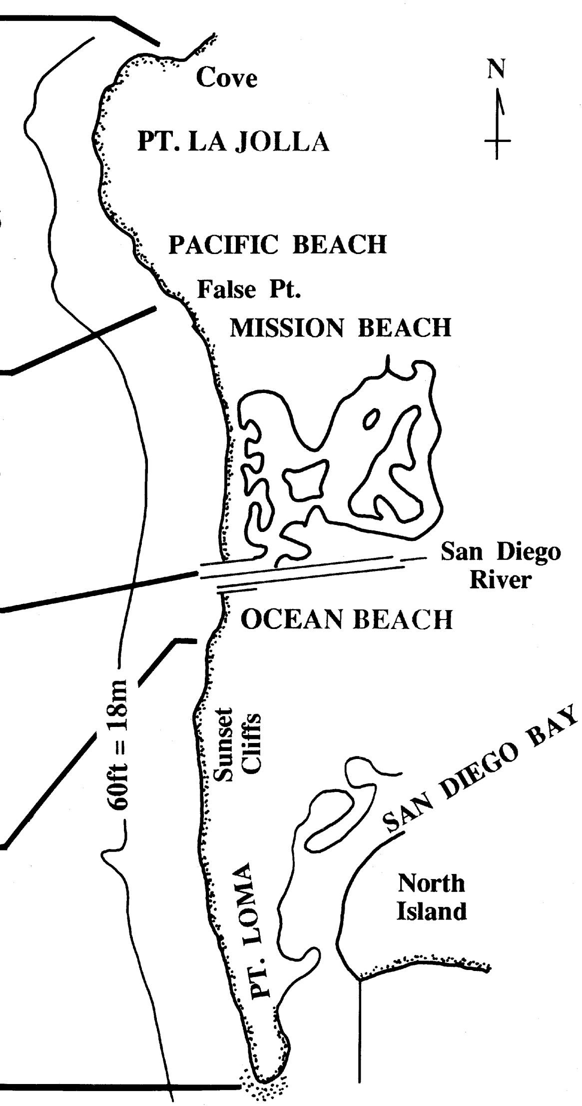


Figure 9-22. (a) Summary of the Budgets of Sediment for Mission Bay Littoral Cell in 10^3 m^3/yr.

91.119-22a

Input or Output		Uniform NW Wave Climate ca.1960-1978 Input	Uniform NW Wave Climate ca.1960-1978 Output	Variable W Wave Climate ca.1983-1990 Input	Variable W Wave Climate ca.1983-1990 Output	SUBCELL	km	mi
Q_n	Longshore	0	5	0	0	PT. LA JOLLA	5.8	3.6
Q_r, Q_s	River, Canyon	0	5	0	15			
Q_b, Q_o	Bluff, Offshore	10	0	15	0			
Q_a	Nourish	0	0	0	0			
$\partial V'/\partial t$ (10^3 yd^3/yr)		**0 balance**		**0 balance**				
Q_n		5	5	0	0	MISSION BEACH	5.8	3.6
Q_r, Q_i	River, Inlet	5	5	5	5			
Q_b, Q_o		0	0	0	0			
Q_a		35	15	5	15			
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+20**		**-10**				
$\partial X/\partial t$ (ft/yr)		**0.6 accretion**		**0.3 erosion**				
Q_n		5	15	0	0	OCEAN BEACH	1.2	0.8
$Q_r + Q_i$		15	5	10	5			
$Q_b + Q_o$		0	0	0	0			
Q_a		15	5	0	5			
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+10**		**0**				
$\partial X/\partial t$ (ft/yr)		**1.4 accretion**		**balance**				
Q_n		15	15	0	0	PT. LOMA	9.7	6.0
Q_r		0	0	0	0			
Q_b, Q_o		25	15	25	15			
Q_a		0	0	0	0			
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+10**		**+10**				
Offshore		**accretion**		**accretion**				
							22.5	14.0

Episodic Beach Erosion: **1982/83 Cluster Storms**

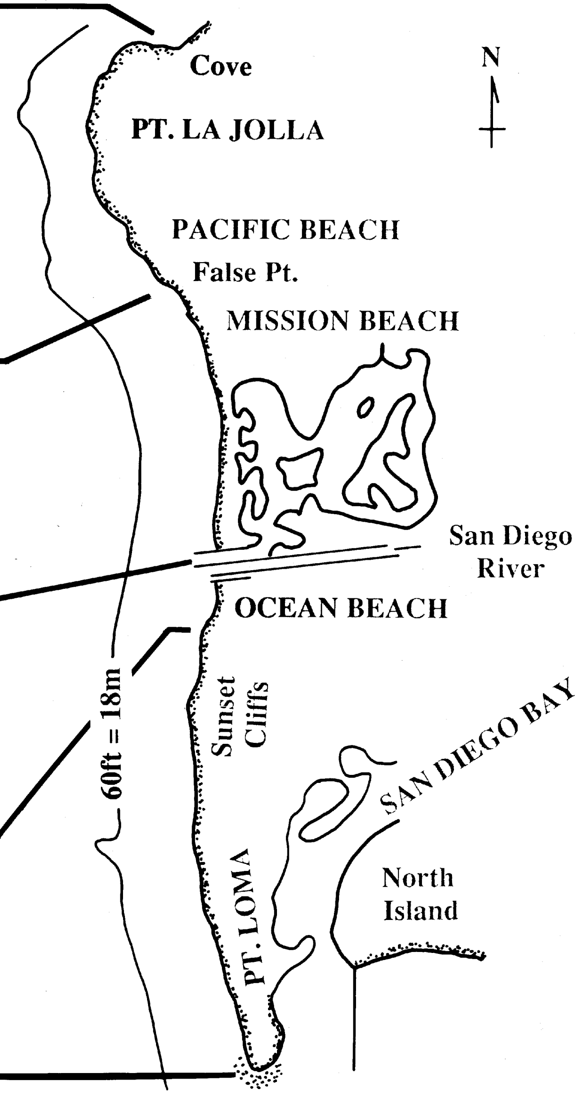


Figure 9-22. (b) Summary of the Budgets of Sediment for Mission Bay Littoral Cell in 10^3 yd^3/yr.

91.119-22b

(2) A better method of kelp removal is needed to avoid sand mining from the beaches.

9.9.4 Silver Strand Littoral Cell

This littoral cell had as a "sole source" the yield of sediment from the Tijuana River, which is now dammed and no longer a viable source. The beaches have been maintained by massive injections of over 26 million m^3 (34 million yd^3) of "new source" nourishment. The rate of nourishment from 1946 to 1985 was over 600,000 m^3/yr (800,000 yd^3/yr). Significant erosion now exists in the vicinity of the Tijuana River delta, and it is progressing both north towards Coronado and south into Mexico. Clearly this cell will require continued nourishment at rates nearing those of the past. Fortunately much of the sand remains in deposits at Zuñiga Shoals and in deeper water off the entrance to San Diego Bay. Budget details and amounts of material involved are summarized in Figure 9-23. These budgets serve as the basis for the necessary ongoing study and planning required to maintain the beaches of the Silver Strand Cell.

Specific Studies

(1) Sand nourishment is by far of first order importance here. Detailed analysis must begin of the sand volumes in Zuñiga Shoals and in the deposits at depths of 18 to 30 m (60-100 ft) off the entrance to San Diego Bay. The submerged Tijuana River delta is now mostly cobble and boulder and not a source of sand.

(2) This source study should be paralleled by study of the economics and methods of transporting the sand to nourishment points.

Input or Output		Pre-Dam Conditions ca.1905-1936 Input	Output	Uniform NW Wave Climate ca.1950-1978 Input	Output	Variable W Wave Climate ca.1983-1990 Input	Output	SUBCELL	km	mi
Q_l+Q_n	Longshore (north)	130	0	130	0	130	0			
Q_r, Q_i	River, Inlet	0	750	0	130	0	130			
Q_{on}, Q_w	Onshore, Wind	0	0	0	0	0	0			
Q_a	Nourish	0	0	0	0	0	0			
$\partial V'/\partial t$ (10^3 m^3/yr) Zuñiga Shoal		**-620 erosion**		**0 balance**		**0 balance**		ZUNIGA	4.3	2.6
Q_l+Q_n	(north)	150	130	50	130	50	130			
Q_r, Q_i		0	0	0	0	0	0			
Q_{on}, Q_w		0	20	0	20	50	20	STRAND	10.1	6.3
Q_a		0	0	630	0	20	0			
$\partial V'/\partial t$ (10^3 m^3/yr) $\partial X/\partial t$ (cm/yr)		**0 balance**		**+530 375 accretion**		**-30 21 erosion**				
Q_l+Q_n	(north)	0	150	0	50	0	50			
Q_l+Q_n	(south)	0	50	0	150	0	50			
Q_r+Q_i		200	0	50	0	50	0			
$Q_{on}+Q_w$		0	0	100	0	0	0	DELTA	7.6	4.7
Q_a		0	0	0	0	0	0			
$\partial V'/\partial t$ (10^3 m^3/yr) $\partial X/\partial t$ (cm/yr)		**0 balance**		**-50 47 erosion**		**-50 47 erosion**				
Q_l+Q_n	(south)	50	50	150	150	50	75	PLAYA DE TIJUANA	4.5	2.8
Q_r, Q_i		0	0	0	0	0	0			
Q_{on}, Q_w		0	0	0	0	0	0			
Q_b	Bluff	0	0	0	0	10	0			
$\partial V'/\partial t$ (10^3 m^3/yr) $\partial X/\partial t$ (cm/yr)		**0 balance**		**0 balance**		**-15 24 erosion**				
									26.5	16.4

Episodic Beach Erosion: **1939 Tropical Storm** (between Pre-Dam and Uniform NW periods); **1982/83 Cluster Storms** (between Uniform NW and Variable W periods)

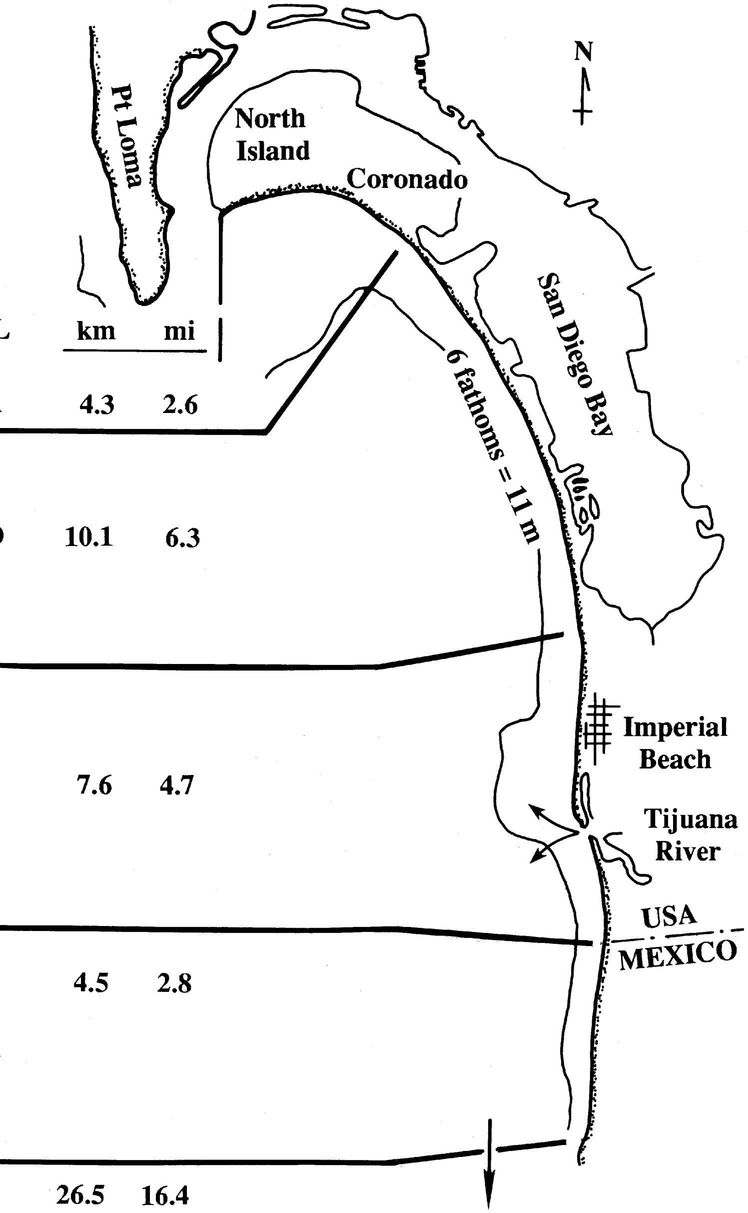


Figure 9-23. (a) Summary of the Budgets of Sediment for Silver Strand Littoral Cell in 10^3 m^3/yr.

91.119-23a

Input or Output		Pre-Dam Conditions ca.1905-1936 Input	Pre-Dam Conditions ca.1905-1936 Output	Uniform NW Wave Climate ca.1950-1978 Input	Uniform NW Wave Climate ca.1950-1978 Output	Variable W Wave Climate ca.1983-1990 Input	Variable W Wave Climate ca.1983-1990 Output
Q_l+Q_n	Longshore (north)	170	0	170	0	170	0
Q_r, Q_i	River, Inlet	0	980	0	170	0	170
Q_{on}, Q_w	Onshore, Wind	0	0	0	0	0	0
Q_a	Nourish	0	0	0	0	0	0
$\partial V'/\partial t$ (10^3 yd^3/yr) Zuñiga Shoal		**-810 erosion**		**0 balance**		**0 balance**	
Q_l+Q_n	(north)	200	170	65	170	65	170
Q_r, Q_i		0	0	0	0	0	0
Q_{on}, Q_w		0	25	0	25	65	25
Q_a		0	0	820	0	25	0
$\partial V'/\partial t$ (10^3 yd^3/yr)		**+5**		**+690**		**-40**	
$\partial X/\partial t$ (ft/yr)		**≈ balance**		**12 accretion**		**0.7 erosion**	
Q_l+Q_n	(north)	0	200	0	65	0	65
Q_l+Q_n	(south)	0	65	0	200	0	65
Q_r+Q_i		260	0	65	0	65	0
$Q_{on}+Q_w$		0	0	130	0	0	0
Q_a		0	0	0	0	0	0
$\partial V'/\partial t$ (10^3 yd^3/yr)		**-5**		**-70**		**-65**	
$\partial X/\partial t$ (ft/yr)		**≈ balance**		**1.7 erosion**		**1.6 erosion**	
Q_l+Q_n	(south)	65	65	200	200	65	100
Q_r, Q_i		0	0	0	0	0	0
Q_{on}, Q_w		0	0	0	0	0	0
Q_b	Bluff	0	0	0	0	15	0
$\partial V'/\partial t$ (10^3 yd^3/yr)		**0**		**0**		**-20**	
$\partial X/\partial t$ (ft/yr)		**balance**		**balance**		**0.8 erosion**	

Episodic Beach Erosion: **1939 Tropical Storm** **1982/83 Cluster Storms**

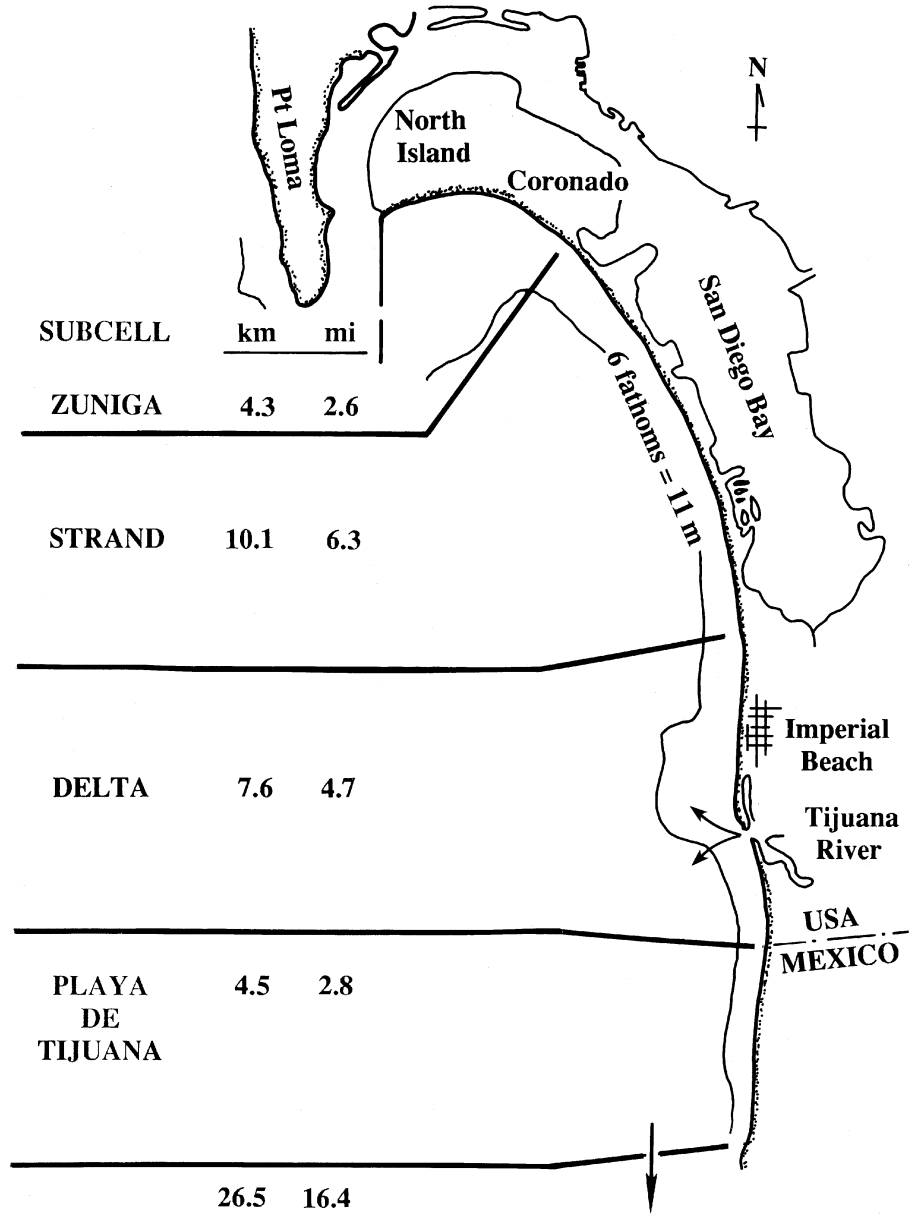


Figure 9-23. (b) Summary of the Budgets of Sediment for Silver Strand Littoral Cell in 10^3 yd^3/yr.

91.119-23b

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