DEVELOPMENT OF SAND BUDGETS FOR CALIFORNIA'S MAJOR LITTORAL CELLS

EUREKA, SANTA CRUZ, SOUTHERN MONTEREY BAY, SANTA BARBARA, SANTA MONICA (INCLUDING ZUMA), SAN PEDRO, LAGUNA, OCEANSIDE, MISSION BAY, AND SILVER STRAND LITTORAL CELLS

KIKI PATSCH
GARY GRIGGS

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INSTITUTE OF MARINE SCIENCES
UNIVERSITY OF CALIFORNIA, SANTA CRUZ
CALIFORNIA DEPARTMENT OF BOATING AND WATERWAYS
CALIFORNIA COASTAL SEDIMENT MANAGEMENT WORKGROUP

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By

Kiki Patch
Gary Griggs

Institute of Marine Sciences
University of California, Santa Cruz
California Department of Boating and Waterways
California Coastal Sediment Management WorkGroup

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Kiki Patsch
Gary Griggs

Institute of Marine Sciences

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ABSTRACT

Sand moves along the coast of California, under the influence of waves, feeding California's intensively used beaches. The consequences of interrupting littoral drift through the construction of jetties, breakwaters and groins, are well known along California's coast. Construction of the Santa Barbara Harbor (initiated in 1927) and the consequent interruption of littoral drift was perhaps the first well-studied example. Average annual dredging volumes at some harbors now reach over 1,000,000 yds^3 annually with costs in excess of $1,000,000. A regional understanding of littoral cell boundaries and sand budgets is an important tool in coastal land use management and coastal engineering, and it is an essential step in understanding sand routing along the coast. Long-term average annual dredging volumes can provide useful proxies for littoral drift rates at specific locations within littoral cells. Many harbors function as efficient littoral drift traps, such that average annual dredging volumes are among the most representative and reliable values we have for the littoral drift rates within individual littoral cells.

In this study, sand budgets were developed for all of California's major littoral cells (including the Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica (including Zuma), San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells) using all available historic data on natural sand inputs, sand losses and beach nourishment, in addition to long-term dredging volumes. Estimates were made of the anthropogenic reductions to the sand supply in these littoral cells due to the damming of rivers, armoring of seacliffs, and mining of beach sand. Overall, damming of rivers has resulted in the reduction of about 23% of the natural sand supplied to the coast, a volume over ~2,500,000 yd^3/yr. The armoring of seacliffs has reduced the sand supply to these littoral cells from cliff and bluff erosion by 11% or ~43,000 yd^3/yr. Sand mining from the beaches of southern Monterey Bay took place until ~1985 at a rate of about 180,000 yd^3/yr but was terminated in the 1980's with only a single sand plant still operating, which now removes about 130,000 yd^3/yr.

Beach nourishment has added ~1,338,000 yd^3/yr on average to the overall sand budget for California's major littoral cells, all of this along the Southern California shoreline. Beach nourishment alone, however, has not completely supplemented or replaced the volume of sand prevented from reaching the beaches through damming and armoring seacliffs; excluding additional losses from sand mining, there remains a statewide, net deficit on the order of ~1,245,000 yd^3/yr, primarily along the southern California coastline.

Overview

The beaches of southern California are intensively used recreational areas generating billions of dollars of direct revenue annually (King, 1999). These wide, sandy beaches, used by people playing volleyball and sunbathing, are the quintessential picture of southern California. Wide, sandy beaches, however, were not always the natural condition in southern California. Many of these beaches have been artificially created and maintained through human intervention, including placement of massive amounts of sand and the construction of groins, jetties and breakwaters (Wiegel, 1994; Flick, 1993). Without human influence, the beaches along this coastline would be, for the most part, narrow and difficult to access. The narrow, marginal beaches would be insufficient for the recreational demands imposed on the shoreline today. The rate of nourishment, however, has been diminishing over the past 30 years, fueling the public's perception of rapid beach erosion and the narrowing of the beaches. In many places, the beaches are merely returning to their natural, non-nourished state. Sand sources for most of the littoral cells in southern California are minimal to begin with, and have been reduced further through the damming of rivers, armoring of seacliffs, and reductions in beach nourishment projects.

Sand is naturally supplied to the beaches of California's littoral cells or beach compartments from a combination of rivers, seacliff erosion, dune deflation or erosion, as well as gullying and erosion of upland materials. In addition, sand has been added to the beaches historically through beach nourishment. In this study, sand budgets were developed for the major littoral cells in California (including the Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica [including the Zuma Beach cell, now recognized as distinct from the Santa Monica cell], San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells) to determine the relative importance of each sand source and the extent to which the sand supplied to these cells has been reduced through the armoring of seacliffs, damming of rivers and mining of beach sand.

Magoon and Lent (2005) have also recently summarized what is known about sand and gravel mining in California streams, which represents a potential long-term loss of sand to the shoreline. They have determined that a total of about 50 million yds^3 of sand and gravel are removed annually through streambed mining. It is unclear, however, how much of this material would naturally be delivered to the coast. These losses have not been included in the individual littoral cell budgets.

Inman and Chamberlin (1960) and Inman and Frautschy (1966) initially developed the concept of littoral cells or beach compartments, and delineated individual cells along the southern California coast. Habel and Armstrong (1978) subsequently made an attempt to divide up almost the entire California coast into littoral cells, although for the central and northern portions of the state, there was no cell by cell research carried out to verify the cell boundaries or whether the cells they labeled existed as self contained compartments. We now know, for example, that some of the cells they defined do not exist and that these areas are parts of adjacent cells (the "Half Moon Bay cell", for example, is not a separate cell but the northern portion of the Santa Cruz cell). There are other cells (the Zuma cell or sub-cell), for example, that we believe are distinct compartments, but which in 1978, were shown as part of the larger cells (in the case of the Zuma cell, it was included as part of the Santa Monica cell). For these reasons, and because some of the cells are either poorly defined or understood (most of the cells north of San Francisco, for example) we focused our efforts on the major littoral cells where we felt there was a combination of available information or coastal sediment management interest. Unless there were agreed upon changes in littoral cell boundaries, as described above, however, we used the boundaries originally listed in Habel and Armstrong.

Individual sand budgets for the major littoral cells are presented in Chapters 2-10. Table i gives an overview of the relative importance of sand sources for each littoral cell in addition to the overall importance of each component to the littoral cells in California. Under present, dammed conditions, (excluding beach nourishment) fluvial inputs constitute about 87% of the sand entering California's major littoral cells, and contribute 90% of the sand to southern California (from the start of the Santa Barbara littoral cell to the international border). On a state-wide basis, contributions to beach sand from seacliff erosion tend to be much less than those from streams. However, such contributions may be very important locally where very sandy cliffs are rapidly eroding and there are no large streams (Runyan and Griggs, 2003). For example, while bluff erosion contributes less than one percent of the sand to the Santa Barbara littoral cell, bluff erosion is believed to contribute about 31% and 60% of the sand to the Laguna and Mission Bay littoral cells, respectively. Also, recent research in the Oceanside littoral cell, utilizing composition of sand in the bluffs and beaches, as well as very precise LIDAR measurements of coastal bluff retreat (over a relatively short 6-year period) concluded that bluffs may contribute 50% or more of the sand to beaches in this littoral cell.

Dune deflation or erosion, statewide, accounts for 8% of the littoral sand (excluding beach nourishment). When beach nourishment is taken as a contributing source of sand, the relative importance of rivers, bluffs, and dunes statewide drops to 72%, 4% and 7% respectively in California's major littoral cells with beach nourishment accounting for the remaining 17% of the sand. In southern California, beach nourishment represents 31% of the sand supplied to the beaches, thus reducing the importance of river and bluff inputs to 62% and 7% respectively.

Table ii is a summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California, and to southern California specifically (from Santa Barbara to the international border) due to the armoring of seacliffs and the damming of rivers in addition to the sand supplied through beach nourishment. Sand bypassing at harbor entrances is not included in the nourishment volume because this is sand that is already in the system and is essentially just being moved within the cell. The greatest reduction in the sand supplied to southern California is from the damming of the rivers, which contribute the majority of sand to the littoral cells. Damming has reduced the sand reaching the beaches in southern California by 47% of the natural fluvial sand yield, which totals nearly 2.3 million cubic yards of sand annually. Seacliff armoring has reduced the sand supplied to southern California's beaches by 10% of the natural sand supply which is over 35,000 cubic yards annually, accounting for less than 7% of the total sand input.

UNCERTAINTIES INVOLVED IN DEVELOPING LITTORAL CELL BUDGETS

While California's littoral cells or beach compartments were first recognized over 40 years ago (Inman and Frautschy, 1966), the development of detailed budgets for individual cells has not progressed very far for many reasons. There are not only major challenges in quantifying the individual source, sink and littoral drift components of individual cells, there are still fundamental uncertainties and lack of agreement regarding both the specific boundaries of some littoral cells, as well as the directions of littoral transport at specific locations.

In this report we have attempted to compile and evaluate all of the existing published sediment data for California's major littoral cells. From north to south these include: Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica (including Zuma), San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells. This in itself was a major undertaking (see References).

Streams provide the great majority of sand to California's beaches (~71% on a statewide basis) and this component is, therefore, one of the most important to quantify. Fluvial sediment transport research, however, shows that sediment transport is very episodic, even within a single year (Griggs, 1987a). In addition, there are very large differences in fluvial sand delivery in El Niño vs. La Niña years (Inman and Jenkins, 1999). Thus the time span covered by the steam gauging record on any individual stream, as well as the difficulties involved in accurately measuring coarse sediment transport, par-

Littoral Cell	All Sand Volumes in yd3/yr	Rivers	Bluff Erosion	Dunes	Beach Nourishment	Total Sand Supply
Eureka	Total "Actual" sand contribution	2,301,000	0	175,000	0	2,476,000
	% of Budget	93%	0%	7%	0%	100%
Santa Cruz	Total "Actual" sand contribution	190,000	33,000	0	0	223,000
	% of Budget	85%	15%	0%	0%	100%
Southern Monterey Bay	Total "Actual" sand contribution	489,000	0	353,000	0	842,000
	% of Budget	58%	0%	42%	0%	100%
Santa Barbara	Total "Actual" sand contribution	2,167,000	11,000	0	0	2,178,000
	% of Budget	99%	1%	0%	0%	100%
Santa Monica	Total "Actual" sand contribution	70,000	148,000	0	526,000	744,000
	% of Budget	9%	20%	0%	71%	100%
San Pedro	Total "Actual" sand contribution	278,000	2,000	0	400,000	680,000
	% of Budget	41%	0%	0%	59%	100%
Laguna	Total "Actual" sand contribution	18,000	8,000	0	1,000	27,000
	% of Budget	66%	31%	0%	4%	100%
Oceanside	Total "Actual" sand contribution	133,000	55,000	0	111,000	299,000
	% of Budget	23%	9%	0%	19%	51%*
Mission Bay	Total "Actual"sand contribution	7,000	77,000	0	44,000	128,000
	% of Budget	5%	60%	0%	35%	100%
Silver Strand	Total "Actual"sand contribution	42,000	0	0	256,000	298,000
	% of Budget	14%	0%	0%	86%	100%
Total	Total "Actual" sand contribution	5,695,000	335,000	528,000	1,338,000	7,896,000
	% of Budget	72%	4%	7%	17%	100%
Southern CA Total: (Santa Barbara cell to Mexico)	Total "Actual" sand contribution	2,715,000	301,000	0	1,338,000	4,354,000
	% of Budget	62%	7%	0%	31%	100%
Total: Without Beach Nourishment	All	87%	5%	8%	N/A	6,558,000
	Southern CA	90%	10%	0%	N/A	3,016,000

Table i: Summary of the average annual (post-damming and seacliff armoring) sand contributions from rivers, seacliff erosion, dune recession, and beach nourishment to the major littoral cells in California. * Gully erosion and terrace degradation accounts for the remaining 40% of the sand in the Oceanside littoral cell. This category is not accounted for in this table. Nourishment data is for the period 1930–1993. (For data sources see Patsch and Griggs, 2006)

Littoral Cell		Rivers (dams)	Bluff Erosion (armor)	Total Reduction	Beach Nourishment	Balance (nourishment-reductions)
Eureka	Reduction yd^3/yr	N/A	N/A	N/A	0	N/A
	Percent Reduction	N/A	N/A	N/A		
Santa Cruz	Reduction yd^3/yr	6,000	8,000	14,000	0	-14,000
	Percent reduction	3%	20%	6%		
Southern Monterey Bay	Reduction yd^3/yr	237,000	N/A	237,000	0	-237,000
	Percent reduction	33%	N/A	33%		
Santa Barbara	Reduction yd^3/yr	1,476,000	3,000	1,479,000	0	-1,479,000
	Percent reduction	41%	19%	40%		
Santa Monica	Reduction yd^3/yr	29,000	2,000	31,000	526,000	495,000
	Percent reduction	30%	1%	13%		
San Pedro	Reduction yd^3/yr	532,000	0	532,000	400,000	-132,000
	Percent reduction	66%	0%	66%		
Laguna	Reduction yd^3/yr	0	1,000	1,000	1,000	0
	Percent reduction	0%	13%	4%		
Oceanside	Reduction yd^3/yr	154,000	12,000	166,000	111,000	-55,000
	Percent reduction	54%	18%	47%		
Mission Bay	Reduction yd^3/yr	65,000	17,000	82,000	44,000	-38,000
	Percent reduction	91%	18%	50%		
Silver Strand	Reduction yd^3/yr	41,000	0	41,000	256,000	215,000
	Percent reduction	49%	0%	49%		
Total	Reduction yd^3/yr	2,540,000	43,000	2,583,000	1,338,000	-1,245,000
	Percent reduction	43%	11%	39%		
Southern CA Total	Reduction yd^3/yr	2,297,000	35,000	2,332,000	1,338,000	-994,000
	Percent reduction	47%	10%	44%		

Table ii: Summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California, and to southern California specifically, due to the armoring of seacliffs and the damming of rivers in addition to the sand supplied to the cells through beach nourishment (sand bypassing at harbor entrances is not included in the nourishment volume).

ticularly at high discharge when most of the sediment is moved, lead to large uncertainties or error bars in quantifying the largest source of sand to the coastline. Some researchers believe that the values reported for annual fluvial sand delivery should be considered as + or – 30% or more.

Very little research has been carried out on the production of sand by coastal cliff or bluff erosion anywhere on the California coast (Runyan and Griggs, 2003). A detailed LIDAR-based study of sand contributions from bluff erosion along the coastline of the Oceanside cell was just completed (Young and Ashford, 2006). This was a 6 year research project, and while it did refine our previous calculations of the importance of bluff erosion to the Oceanside littoral cell sand budget, it still only covered 50 miles of California's 1100 miles of coastline. Even this detailed study only spans 6 years of relatively mild climatic conditions so that the values determined may be different under more severe weather and storm conditions.

One of the challenges with all of the data we have summarized is that they span different climatic conditions (El Niño vs. La Niña years, for example), and may or may not be representative of long-term conditions. Thus, we are constrained by the historical data that have been collected, which while considerable, still have their limitations. Surprisingly, there are relatively few detailed littoral cell budgets that have been completed in California following the first such effort by Bowen and Inman in 1966. Inman (1976) and Best and Griggs (1991 a, b) are among the few such efforts.

The Santa Barbara littoral cell is one of the earliest (Trask, 1952) and best studied in California, yet despite over 50 years of research, there are still major disagreements as to whether any littoral sand is transported around Pt. Conception, and if so, how much. While the Eureka littoral cell has been much less studied, it receives ~40% of all of the fluvial sand delivered to California's major littoral cells, yet it is not clear how much of this sand moves north, how much moves south, and how much moves offshore after it reaches the shoreline.

Littoral drift rates have been extremely difficult to document or determine. While potential littoral drift rates have been calculated from wave data, these values are extremely sensitive to near shore bathymetry, and also vary seasonally depending upon direction of wave approach. In this report we use harbor dredging rates as a reasonable proxy for littoral drift rates and as a check point in the determination of alongshore littoral drift rates for each major littoral cell. Some harbors, Santa Barbara and Santa Cruz, for example, form nearly complete littoral traps such that long-term average annual dredging rates are believed to be good estimates of net littoral drift at specific locations within a cell. In other locations, Oceanside Harbor, for example, significant volumes of sand have been transported offshore and littoral drift reverses seasonally, which complicates the determination of net littoral drift rates (Seymour and Castel, 1985).

Despite all of these uncertainties, we believe that it is valuable to compile, evaluate and summarize all that we do know about the sand budgets for the state's littoral cells. With the state's increased interest in coastal sediments and the impacts of too little sediment along some shorelines (whether from natural processes or human impacts), and too much in other locations (ports and harbors for example), the Coastal Sediment Management Workgroup was established to carry out the necessary studies to develop a better understanding of California's coastal sediments, their sources, transport, storage and sinks, to aid in sediment management decision making. This report is a companion report to ***Littoral Cells, Sand Budgets, and Beaches: Understanding California's Shoreline*** (Patsch and Griggs, 2006) and is a comprehensive evaluation of what is known about the sand budgets for California's major littoral cells. As this study progressed we identified a number of specific areas where we believe additional information or more detailed studies could provide information useful in developing a better understanding of California's coastal sediment budgets that would be useful in our attempts to better "manage" the state's coastal sediments.

RECOMMENDATIONS FOR FUTURE COASTAL SEDIMENT RESEARCH

Cross-Shore Sediment Transport: Typically cross-shore transport, whether on- or offshore, is the mechanism or process called upon to explain major imbalances in the sand budgets of individual littoral cells. Specific examples where cross-shore transport is used to explain major losses of littoral sediment include the Eureka, southern Monterey Bay and Santa Barbara littoral cells. In the Eureka cell, ~2,300,000 yds^3/yr of sand is discharged annually on average by the Eel River, and it is believed that the majority of this is lost offshore on the continental shelf or deposited into the Eel Submarine Canyon, although the transport paths and processes are not clear. There is also no agreement on how much of the sand in this vicinity moves north and/or south as littoral drift.

In the Southern Monterey Bay littoral cell there appears to be a convergence of littoral drift approximately midway between the head of Monterey Submarine Canyon at Moss Landing and the Monterey peninsula, with general agreement that significant volumes of littoral sand (~187,000 yds^3/yr: Thornton, personal communication; 350,000 yds^3/yr, Smith, et. al. 2005b) are carried across the shelf.

Although the mouth of the Santa Maria River has been used as the northern boundary of the Santa Barbara littoral cell for decades, there has never been agreement, despite a number of sediment transport studies, whether sand from the 46 miles of shoreline between the Santa Maria River and Point Conception is transported around the point or is transported offshore. In order to balance the sediment budget, ~470,000 yds^3/yr of sand appears to be transported offshore at this location.

Each of these three areas represent locations where large volumes of beach sand appear to be transported offshore and out of the littoral zone permanently. Yet detailed studies that document the transport paths, depositional sites or evidence for this mechanism have not been completed. Multibeam studies of these areas could confirm this transport mechanism in these areas and also, in the case of the Pt. Conception and southern Monterey Bay sites, provide evidence or confirmation that these may be potential sites for obtaining sand for potential beach nourishment.

Hyperpycnal and Gravity Flows: Two potential mechanisms for significant sand transport across the shelf are hyperpycnal and gravity flows. Recent work by the US Geological Survey along the southern California coastline (Jon Warrick, personal communication) suggests that sediment can be transported offshore during high discharge or major flooding events. This is an area where continued focused research could prove very fruitful in elucidating the timing, duration and extent of such cross-shore transport.

Sand Impoundment at Large Coastal Engineering Structures: Just as large volumes of potential littoral sediment have been impounded behind California's many coastal dams (Slagel, 2005), large volumes of beach sand have been impounded by California's many groins, jetties and breakwaters for decades. The amount of sand in storage in these locations has never been completely evaluated, but represents a large amount of littoral sand that should be considered as part of any regional sand management plan or potential nourishment program. Some beaches, for example, because of these obstructions are very wide. Could some of this sand be used elsewhere in a cell and stabilized by constructing additional groins? Documenting the history of shoreline accretion at the locations of these large structure and quantifying as accurately as possible the volumes of sand impounded would allow better analysis of littoral cell budgets at these locations and also could provide a potential source of beach nourishment.

One specific example of such an area is the 5-mile reach between the Santa Clara River and the Channel Islands Harbor where there is a 15-year history of accretion, but no overall evaluation of how much total sand has been impounded or how this has changed over time.

Losses of Sand into Submarine Canyon Heads: The most important sink for littoral sand in California are the many submarine canyons that head close to shore and intercept littoral drift. Everts and Eldon (2005) have summarized the information on sand capture by the canyons of southern California, and Smith et. al. (2005a) have recently completed detailed repeat multibeam surveys of the head of Monterey Submarine Canyon that reveal the near-shore part of the canyon is a site of active sediment transport and is in a long-term phase of enlargement. We know little about the remaining canyon heads, however. Because we believe that these are the major sinks for most of California's littoral sand, it would be valuable to image these canyon head areas and document to the extent to which they serve as active sediment sinks and compile all of this information for California's major littoral cells.

Natural Beach Widths and Long-term Beach Width Changes: A study is now being completed that has been partially funded by the University of California Marine Council with assistance from the Department of Boating and Waterways on long-term changes in widths for the beaches of the Santa Barbara, Santa Monica and Zuma, San Pedro, and Oceanside littoral cells. The objectives are to utilize a representative long-term historical set of aerial photographs of the shoreline of these cells to document whether the beach widths have changed systematically over time, and if so, whether the changes have been due to natural cycles and processes (climatic change, for example), anthropogenic activities (dam construction, for example), or a combination. We need to extend these long-term beach width studies to California's other major littoral cells.

In the absence of any major reductions in littoral sand supply (due to either large-scale climatic fluctuations or human activities), beaches over the long-term will tend to approach some equilibrium size or width; e.g. a summer width that will vary about some mean from year to year. This width is a function of a) the available littoral sand, b) the location of barriers or obstructions to littoral transport (Everts and Eldon, 2000; Everts, 2000), c) coastline orientation, and d) littoral drift direction and rate, which is related to the amount of wave energy incident on the beach and the angle of wave approach. There are places in California where the conditions are conducive to the formation of wide beaches, and in these locations there is no significant or regular threat to the back beach landforms (whether dunes, bluffs or cliffs) and associated development. On the other hand, there are many areas where there are either no beaches, or only narrow or seasonal beaches, and where cliff and bluff erosion are ongoing natural processes with ongoing threats to coastal development.

Beach Widths and Cliff/Bluff Profiles: As recommended above, the long-term natural or equilibrium beach widths of the remainder of California's major beach areas (beyond the southern California littoral cells now being studied) need to be measured so that we understand how these vary throughout California's developed and intensively used beach areas. This will provide the fundamental perspective on whether it is reasonable to expect that sand added to particular coastal areas can be expected to remain on the beaches.

Twenty-five years ago, Emery and Kuhn (1982) recognized that the shape or slope of coastal cliffs or bluffs was indicative of whether marine or terrestrial processes dominated in their formation. Vertical or near vertical cliffs are characteristic of those areas where marine processes dominate, where waves regularly reach and undercut the base of the cliff or bluff leading to failure from the bottom up. Cliffs in these locations are very steep as they are constantly being undercut and steepened. Coastlines with steep or near vertical cliffs also appear to be characterized by narrow or non-existent beaches, which is why waves regularly attack these cliffs (Figure i).

On the other hand, where coastal bluffs have a more gentle or convex profile, terrestrial erosional processes dominate, whether runoff and surface erosion, or slumping or landsliding. Terrestrial or subaerial processes thus create very different bluff or cliff profiles and occur where beaches are wide year-round such that the high tides and waves don't reach the base of the bluff (Figure ii). Thus a systematic assessment of the relationship between cliff or bluff slope and the absence or presence of a beach and its width should be carried out as a compliment to assessing long-term beach widths to provide the important background for evaluating whether efforts or plans for beach sand nourishment are likely to be successful.

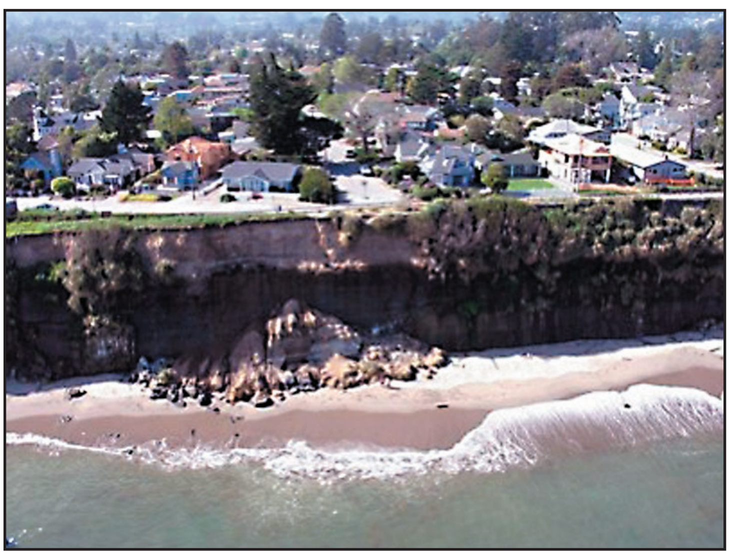

Fig i. Near vertical coastal cliffs in Capitola with narrow beach.

There is a fundamental issue that this apparent relationship raises- those shorelines with wide permanent or year-round beaches are those where beaches are stable and bluff or cliffs are not under any regular wave attack and are, therefore, not undergoing significant retreat at present (Figure ii). On the other hand, those areas where cliffs are being actively eroded by wave attack and undercutting, where homes or cliff top development is being threatened, seem to be those areas where for some combination of reasons listed earlier, there is either a very narrow or only a seasonal beach. These are the areas where wider beaches are needed but under natural conditions, no significant or permanent protective beach has formed.

Fig ii. Gently slope bluff at Manresa Beach with wide protective beach.

There is therefore no reason, based on the existing environmental variables, why sand added to such a coastline should remain there for any significant period of time without some retention structures. We recommend studying the relationship between beach width and cliff or bluff slope as a necessary next step in assessing the potential for effective beach widening through nourishment.

CHAPTER 1

LITTORAL CELLS AND THE DEVELOPMENT OF A SAND BUDGET

Beach compartments or littoral cells form the framework for understanding the sources, transport, sinks and storage of sand in the nearshore zone along the Pacific Coast (Figure 1.1). In a typical beach compartment, littoral transport begins at a rocky headland or section of coast where the upcoast supply of sand or littoral drift is restricted or minimal. Sediments enter the littoral cell primarily from coastal streams and bluff erosion, and are transported alongshore under the influence of the prevailing wave conditions (Inman and Frautschy, 1966). Ultimately, the sand is lost from the system or cell through either a submarine canyon, a coastal dune field, or in some cases, sand mining. Ideally, each cell exists as a distinct entity with little or no transport of sand between cells. Bowen and Inman (1966) completed one of the first sand budgets of a littoral cell and were able to estimate each input and output along the central coast of California, which has proven to be a valuable reference and useful template for subsequent studies.

Lack of a quantitative understanding of littoral cells and sand budgets has become apparent along the California coast (Griggs, 1987b).

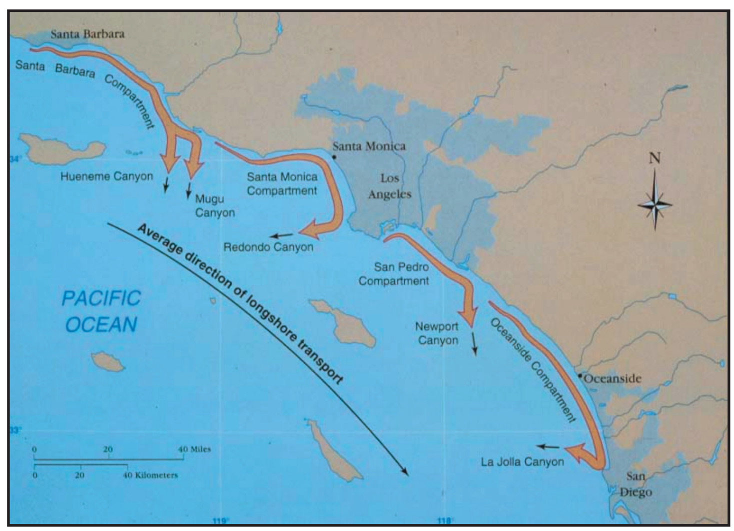

Fig 1.1: Littoral cells in Southern California. (Inman and Chamberlain, 1960; Thurman and Trujillo, 1999)

The problems and costs associated with harbor dredging where jetties or breakwaters have been constructed in the middle or downcoast ends of littoral cells with high drift rates on one hand, and the reduction of sand delivery to beaches due to impoundment of sand behind dams in the coastal watersheds (Brownlie and Taylor, 1981; Ewing et al., 1999; Norris, 1964; Willis et al., 2002) on the other, stem directly from the failure to incorporate this type of information early on in the decision-making process in large coastal engineering projects. The application of a sand budget to the nearshore zone is a useful tool in coastal land use management and coastal engineering, and it is an essential step in understanding sand routing along the coast. On the central and northern California coastline, a large gap exists in the present state of knowledge regarding littoral cell boundaries and production, transport, storage, and loss of littoral sand within these cells.

Along California's 1,100 miles of coast, there are four large harbors (Humboldt Bay, San Francisco Bay, Los Angeles/Long Beach Harbor, and San Diego Bay) and

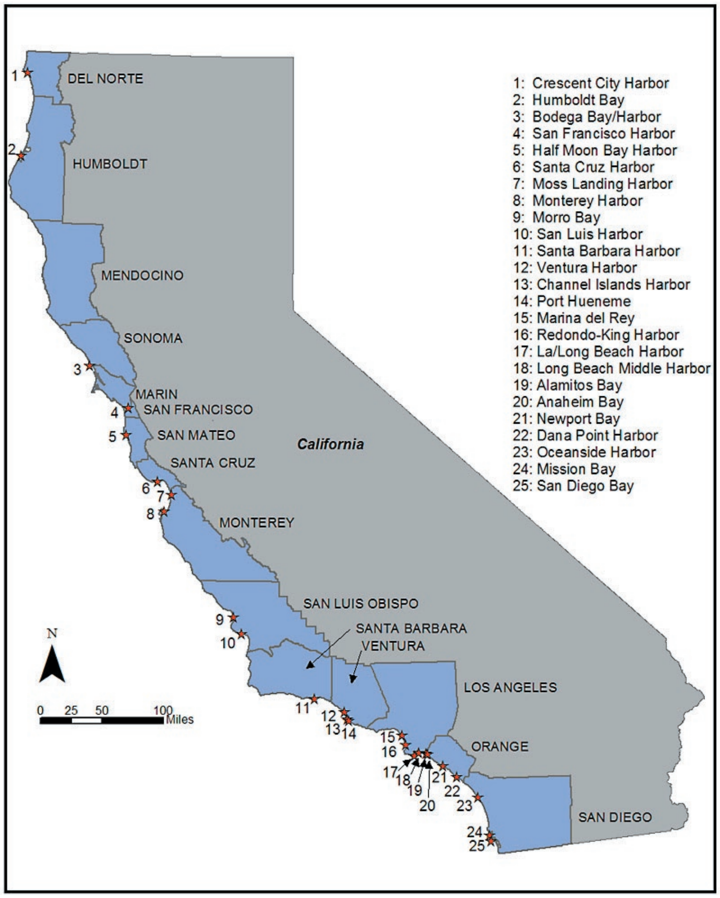

Fig 1.2: California's harbors and littoral cell boundaries. (Source: Modified from Habel and Armstrong, 1978)

21 small craft harbors with some entrance channel or breakwater protection (Figure 1.2). Additional entrance channels and small craft harbors have been proposed and are being considered as well. Each of these existing harbors occupies a position in a littoral cell (Figure 1.4) and has the potential to provide important information on the littoral drift rate or sand transport at that particular location. Although sand inputs to littoral cells from coastal streams and from cliff erosion are difficult to quantify accurately (Griggs, 1987b; Runyan and Griggs, 2002; Willis et al., 2002) due to both spatial and temporal variations in the key quantities measured, long-term average annual dredging volumes can provide a reasonable estimate on gross transport.

The record on dredging in some cases (e.g. Santa Barbara Harbor) extends back over 70 years such that the year-to-year variations can be averaged out, long-term average annual quantity calculated and long-term trends recognized (Figure 1.3). Thirty or more years of dredging data are available for other harbors. Cumulatively, the long-term data on harbor dredging has the potential to be a useful and valuable indicator of littoral drift rates at specific locations along California's 1,100

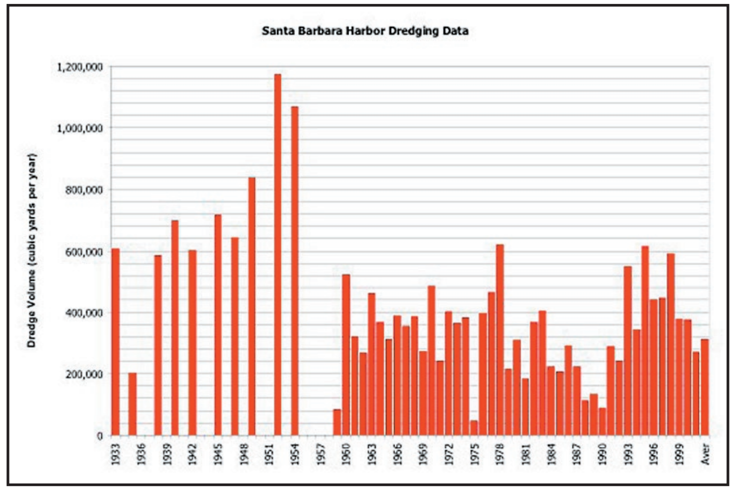

Fig 1.3: Santa Barbara harbor maintenance dredging records: 1933-2001. From 1933 to 1954 dredging of this harbor took place every 2 to 3 years. It is unknown whether data for 1955-1958 are missing or if dredging did not occur.

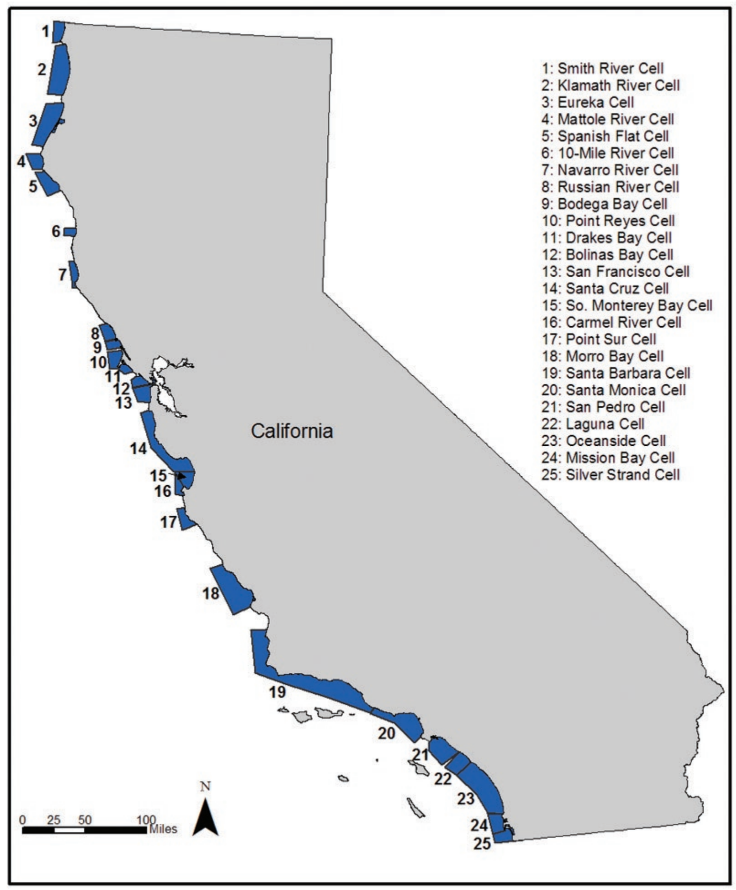

Fig 1.4. California's littoral cells (from Habel and Armstrong, 1978)

miles of coastline. These values can be used to develop sand budgets in order to gain perspective and cross check the other elements in a littoral budget, e.g. the particular input and output volumes from specific sources and sinks (i.e. rivers, cliff erosion, and submarine canyons) that are far more difficult to quantify. Littoral drift data are necessary to evaluate in the preliminary planning for any additional entrance channels or small craft harbors, and can also be used to estimate or predict future dredging costs.

PROCESSES GOVERNING SAND MOVEMENT ALONG THE CALIFORNIA COAST AND THE DEVELOPMENT OF A SAND BUDGET

Along the coast of California, a longshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. Researchers have learned that sand is in constant motion along California's coastline, and only resides "temporarily" on an individual beach. An alongshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. This current and the turbulence of the breaking waves, which serves to suspend the sand, are the essential factors involved in moving sand along the shoreline. As waves approach the beach at an angle, the up-rush of water, or swash, moves sand at an angle onto the shoreface. The backwash of water rushes down the shoreface perpendicular to the shoreline or a slight downcoast angle, thus creating a zigzag movement of sand. This zigzag motion effectively results in a current parallel to the shoreline. Littoral drift refers to the movement of entrained sand grains in the direction of the longshore current.

Littoral drift or transport can occur alongshore in two directions, either upcoast (typically to the north or northwest in California) or downcoast (to the south or southeast), depending on the dominant angle of wave approach. Longshore transport for any particular reach of coast will typically include both upcoast and downcoast transport varying seasonally. Gross littoral drift is the sum of the both components, while net littoral drift is the difference between the drift magnitudes. For example, in California, the more energetic winter waves generally approach from the northwest direction, and drive littoral drift southward along the beaches. During El Niño winters, waves generally come from the west and the southward transport is reduced. Transport is often to the northwest in most of Southern California during the summer months when southern swell dominate. For most of California, from Cape Mendocino south to San Diego, waves from the northwest have the greatest influence on littoral drift, and thus, a nearly unidirectional southward net littoral drift (Figure 1.5) of sand develops (Habel and Armstrong, 1978).

Whereas it is common practice to refer to most beach sediment as "sand", grain sizes on beaches in California range from very-fine sand to cobbles on the widely-used Wentworth scale. The Wentworth scale classifies sediment by size in millimeters based on powers of two. According to this scale, sand is defined as all particles between 0.0625 mm and 2 mm in diameter (Table 1.1). Krumbein (1936) introduced the phi scale as an alternate measure of sediment size based on the powers of two from the Wentworth scale. Phi (Ø) is related to the grain size by the following equation:

$$Ø = -\log_2 d$$

such that $2^{-Ø} = d$, where d is the grain diameter in mm. The phi scale is commonly used in the coastal geology community. It is important to note that larger phi sizes correspond to smaller grain sizes. Very fine-grained sand, ranging from 0.0625 to 0.125 mm in diameter (4Ø to 3Ø), typically doesn't remain on most California beaches due to the high-energy wave environment. Hicks (1987), in

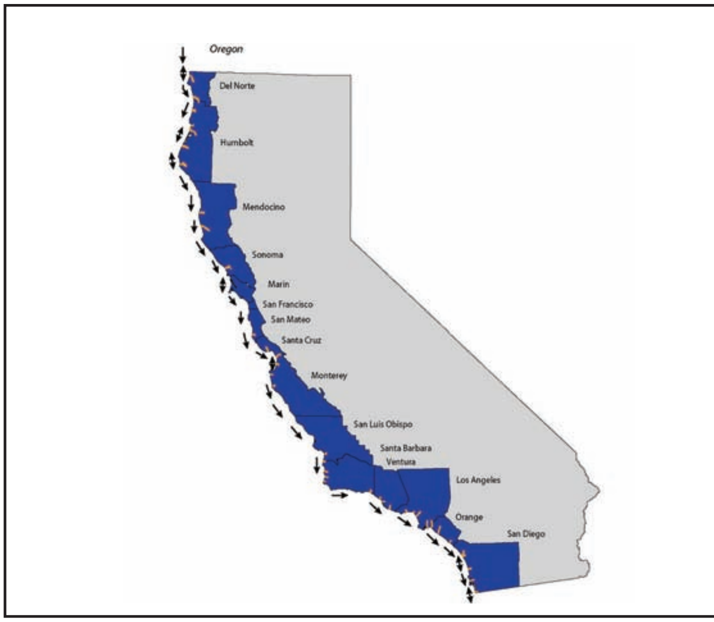

Fig 1.5: Net littoral drift directions in California. (Source: Modified from Habel and Armstrong, 1978)

an investigation of littoral transport processes and beach sand in northern Monterey Bay, discovered that there was a "littoral cut-off diameter", or a grain size diameter, characteristic of particular segments of coast, that serves as a functional grain size boundary in that very little material finer grained than this diameter remains on the beach. The littoral cut-off diameter is primarily a function of wave energy along any particular beach or stretch of coast. Studies along the coast of northern Santa Cruz County (Best and Griggs, 1991b; Best and Griggs, 1991a; Hicks, 1985; Hicks and Inman, 1987), which is a relatively high-energy, exposed coast, indicate a littoral cut-off diameter of ~0.18 mm (2.5Ø), and very little sand finer than this is retained on the exposed beach.

A sand budget employs the conservation of volume concept, and is simply an accounting of the sand entering, leaving, or contained within a study area, in this case a littoral cell (Figure 1.6).

Wentworth Scale Size Description	Phi Units Φ	Grain Diameter (mm)
Boulder	-8	256
Cobble	-6	64
Pebble	-2	4
Granule	-1	2
Very Coarse Sand	0	1
Coarse Sand	1	0.5
Medium Sand	2	0.25
Fine Sand	3	0.125
Very Fine Sand	4	0.0625
Silt	8	0.004
Clay	12	0.00024

Table 1.1: Wentworth scale of sediment size classification.

Dean and Dalrymple (2001) compute sand accumulation in an area, ΔVs, by

$$\Delta Vs = Vx_1 - Vx_2 + Vy_1 - Vy_2 +/- S$$

where

Vx_1 = volume of sand carried into the study area along shore

Vx_2 = volume of sand leaving the study area alongshore

Vy_1 = volume of sand transported into the area from the landward side

Vy_2 = volume of sand going offshore out of the area

S = volume added artificially or removed (mining) within this study area

Change in total sand volume is related to the difference in sand transported into and out of the storage area through longshore or littoral drift, the difference in sand transported to the area from landward sources, such as river discharge and seacliff erosion, and sand transported offshore, as well as sand added artificially to the area, such as beach fill or nourishment, or removed by sand mining (Figure 1.6).

Individual segments of the coast can advance, retreat, or be in a state of equilibrium depending upon the overall sand budget of the area. The response of the coastline is directly related to the volume of sand coming into a system compared to the volume of sand leaving the system. In order to formulate an accurate sand budget, information must be gathered on all the sources and sinks for each segment of coast. In California, the most logical way to compartmentalize the shoreline is to use the previously discussed concept of littoral cells.

Ideally, a littoral cell will start with a rocky promontory or headland, and moving down drift, the beach will gradually

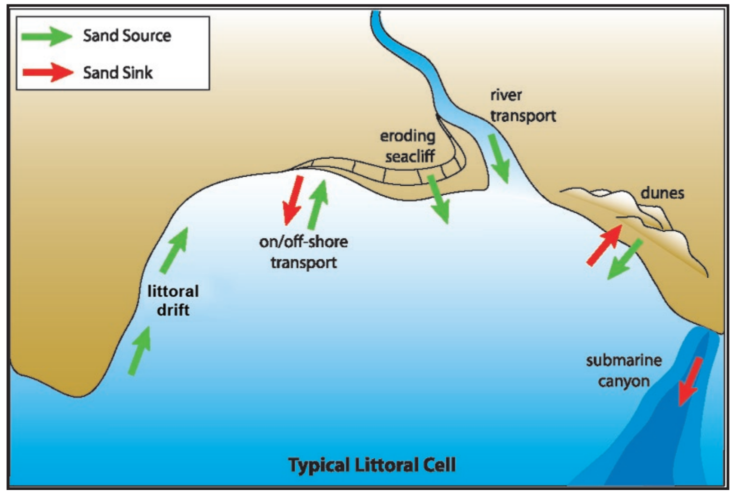

Fig 1.6: Schematic of the principal components that commonly are involved in a sand budget for littoral cells in California (modified from Komar 1996)

widen as sand is added to the cell through some combination of rivers, seacliff erosion, dune recession, gully and terrace degradation, or onshore movement of material from the continental shelf. Sand leaves the system in the form of dune growth, sand mining, offshore movement onto the continental shelf, or when it reaches the terminus of most littoral cells, a submarine canyon (Figure 1.6). Submarine canyons, if located close enough to shore, can effectively trap littoral drift and funnel sand offshore into deep enough water so as to remove the sand permanently from the littoral system. It is the balance of all of these sources and sinks within each littoral cell that governs the width or volume of the beaches in California. If there is a significant reduction in the amount of sand reaching a particular stretch of coast, beaches will narrow or erode. Conversely, if there is increase of sand in a particular area, beaches will typically widen.

COMPONENTS OF A SAND BUDGET

The main challenge in developing a sand budget for a littoral cell is quantitatively assessing all the sources and sinks to a reasonable degree of accuracy (Komar, 1996). For the purposes of this report, a thorough literature search was done to get the most up to date information on each component of the sand budgets. In addition, calculations were made for sand contributions from seacliff erosion in many of the littoral cells. Perhaps not surprisingly, new information has been developed during the course of this study, or brought to our attention by reviewers that have modified our earlier findings and conclusions.

River Inputs (Source): Rivers contribute the great majority of sand to the beaches in California. Willis et al. (2002) recently determined the sand contribution for the majority of the coastal rivers and streams in California using the daily measured values of water discharge or probabilities of discharge events (available in the Water Supply Papers of the U.S. Geological Survey) to develop sediment-rating curves for sand-transport loads. These rating curves were then used to evaluate the total sediment yield each year from the rivers and streams. Average sand yields (sediment that is sufficiently coarse to remain on the beach) were then calculated from these data for most of the rivers and streams in California. Willis et al. (2002) determined that approximately 11,000,000 cubic yards of sand is being delivered annually to the coast of California from 37 rivers and streams. This methodology is the most reliable process to determine the sand contribution from rivers; however it is not without inherent errors. Gauging stations are often well upstream from river mouths; thus, sediment loads may change between the gauging station and the delivery to the shore.

Sand delivery by rivers to California littoral cells has also been shown to be extremely episodic (Griggs, 1987a). Most of the sand for any particular stream is discharged during several days of high flow each year. Additionally, sand discharge during a single year of extreme flood conditions may overshadow or exceed decades of low or normal flow. The Eel River transported 57,000,000 tons of suspended sediment on December 23, 1964, 18% of the total sediment load of the river during the previous ten years. This one-day discharge was greater than the average annual suspended sediment discharge of all of the rivers draining onto the entire California coastline (Brownlie and Taylor, 1981; Griggs and Hein, 1980). However, on some streams, little or no sediment discharge data may exist for the flood or large discharge events that transport the greatest volumes of sediment. As a result, rating curves may not adequately predict sand transport from water discharge records during the high discharge events when most sediment is transported.

Fluvial sediment discharge has also been shown to vary widely from El Niño to La Niña periods (Inman and Jenkins, 1999), such that the length of historic streamflow record from any particular gage may or may not be representative of long-term conditions. In Southern California, mean annual stream flow during wet El Niño periods exceeded that during the dry periods by a factor of about three, while the mean annual suspended sediment flux during the wet periods exceeded the sediment transported during dry periods by a factor of about five (Inman and Jenkins, 1999).

At their best, data on fluvial sand discharge are believed accurate to within about 30% to 50% (Willis and Griggs, 2003). Yet, the amount of sand transported and delivered to the shoreline by streams is an extremely important component of all sand budgets for California.

Seacliff erosion (Source): Seventy-two percent of California's 1,100-mile coast consists of seacliffs. More specifically, 59% of the coast consists of actively eroding wave-cut bluffs or terraces, which when eroded contribute sand for California's beaches. Runyan and Griggs (2002) determined the annual sand contribution from seacliff erosion for two littoral cells in California as part of a beach restoration study with the California Coastal Conservancy. The annual production of littoral sand from a segment of coastline through seacliff erosion (Qs) is the product of the cross-sectional area of seacliff (Area = alongshore cliff length x cliff height), the average annual rate of cliff retreat, and the percentage of the material that is littoral-sized (Figure 1.7):

$$Qs\ (ft3/yr) = Lc*E*(Hb*Sb + Tt*St)$$

in which Lc is the alongshore length of the cliff (ft); E is the erosion rate (ft/yr); Hb is the bedrock height (ft); Sb is the percentage by volume of beach-size material in the bedrock; Tt is the thickness of the terrace deposit (ft); and St is the percentage by volume of beach-size sand in the terrace deposit.

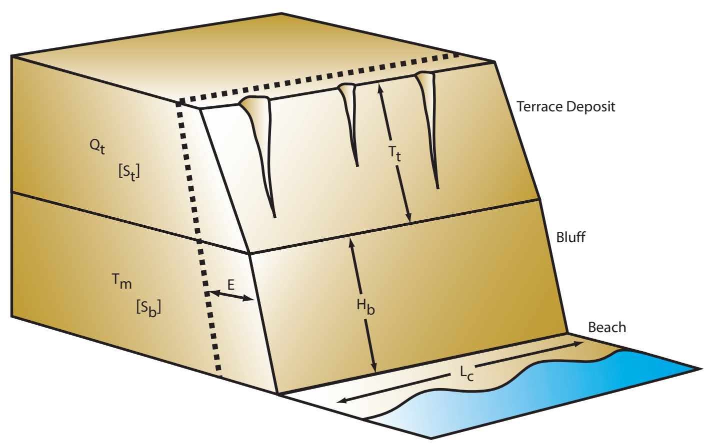

Fig 1.7 Seacliff showing the components involved in calculating sand contributions: Le is the alongshore length of the cliff (ft); E is erosion rate (ft/yr); Hb is bedrock height (ft); Sb is percentage of sand size material larger than the cutoff diameter in the bedrock; Tt is thickness of the terrace deposit (ft); and St is percentage of sand larger than the cutoff diameter in the terrace deposit. Tm (Tertiary Marine) represents geology of the bedrock and Qt (Quaternary Terrace represents geology of the capping terrace deposit.

The geology of the seacliffs along the coast of California varies widely alongshore and, therefore, all of these parameters vary from location to location. Typically, where the coastal cliffs consist of uplifted marine terraces, there is an underlying, more resistant bedrock unit, which may vary widely in composition, and an overlying sequence of sandy marine terrace deposits, which consist predominantly of relict beach sand. Each unit must be analyzed for its individual sand content. In order to make qualitative assessments or quantitative measurements of the contribution of coastal cliff retreat to the littoral system, it is necessary to divide the coast into manageable segments that are somewhat uniform in morphology and rock type. The estimates of sand contributions from the individual segments can then be added to arrive at a total contribution to the beach for a larger area, such as a specific littoral cell (Best and Griggs, 1991b; Best and Griggs, 1991a; Diener, 2000; Runyan and Griggs, 2002).

The methodology for determining sand contribution from seacliff erosion is much simpler than that for determining river contributions; however, these estimates still have a high degree of uncertainty. The most difficult element of this methodology to constrain is the long-term seacliff erosion rates, due to the high spatial variability and episodic nature of seacliff failure (Komar, 1996). There are many areas of the California coast where cliff erosion data have never be determined. Additionally, the amount of littoral sized sand contained in the bluffs of any particular area and will range widely. Relatively few grain size analyses have been carried out for bluff forming materials (Runyan and Griggs, 2002) along California's coastline so data on littoral sand contributions to the beach are limited. The higher the density of sampling for grain size analysis along any stretch of coast, and the more uniform the bluff forming materials, the more reliable will be the calculations of cliff or bluff contributions to the beaches of the cell.

Cross-shore exchange (Source/Sink): Potential exchange of sand between the nearshore and the continental shelf is the most difficult and poorly evaluated element in sand budgets. Cross-shore transport can represent a net gain or loss for the beach. A comparison of sand composition between nearshore and shelf sand is often used as evidence for a net onshore or offshore transport; however, the similarity in composition can only indicate that an exchange has taken place. It rarely indicates direction of transport or volumes of sand moved, which are necessary for development of a sand budget. Komar (1996) states that "… this component within the total budget remains the most poorly evaluated, and in many cases it can only be argued that this exchange between the beach and the offshore must be small compared with the other components within the budget." Recent studies in several different coastal environments have shown that net cross-shore transport can be a significant portion of the total sand budget for a particular area over decadal time scale, however. For the purposes of this research, net cross-shore exchange of sand is assumed to be zero, such that the volume of sand transported on- and offshore are balanced, unless otherwise noted. This is an area where field experiments and modeling studies could help in resolving or quantifying this component of littoral sediment budgets.

Dune Growth/Recession (Sink/Source): Wind action primarily carries sand inland from the beaches and deposits it as a foredune or within a larger dune complex (Johnson, 1959; Komar, 1996). In many areas of California, such as the Eureka and the Santa Barbara littoral cells, sand dunes constitute a significant sink to the cell (Bowen and Inman, 1966; Winkelman et al., 1999). Dune migration and growth can be measured from aerial photographs; these rates can be converted into sand volumes by measuring the dune width and height. Although it is most common that dunes are a sink in a littoral cell budget, sand may be blown onto the beach from an inland area representing a source of sand. Dune growth and deflation often introduces a time element into a littoral cell sand budget. One major storm can erode foredunes, which were previously considered a sink, returning the sand to the beach. However, many studies have concluded that this type of foredune erosion may occur for only a few days during a major storm event, and is subsequently followed by a prolonged period (from years to decades) of foredune growth (Komar, 1983; Komar, 1996; Thom and Hall, 1991).

Losses into Submarine Canyons (Sink): Submarine canyons that extend close to shore (such as Monterey, Mugu, Redondo and La Jolla submarine canyons; Figure 1.8) can serve as effective barriers to littoral drift and terminate most littoral cells in California (Griggs, 1985; Griggs, 1987b; Inman and Chamberlain, 1960; Komar, 1996).

Fig 1.8: Monterey Submarine Canyon

Recent high-resolution multibeam bathymetry in the head of the Monterey Submarine Canyon clearly shows the pathways for sand from the shoreline into the canyon (Figure 1.9). Sand typically accumulates in the canyon head until severe storms excite high magnitude oscillatory flows within the canyon that initiate turbidity currents, which transport sediment downslope and offshore into depths of water where it is no longer a viable part of the nearshore system (Johnson, 1959; Seymour, 1986; Shepard, 1951).

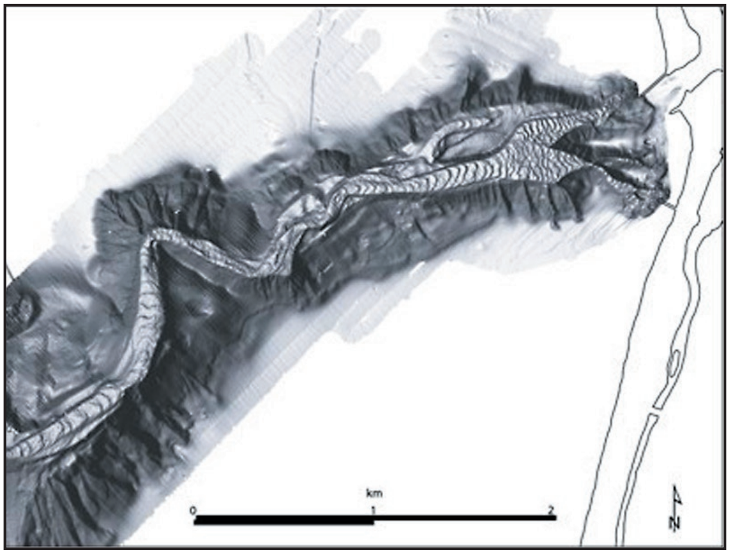

Fig 1.9. Sand waves in the head of Monterey Submarine Canyon (from Doug Smith, CSU Monterey Bay)

Inman and Chamberlain (1960) determined that approximately 200,000 cubic yards per year of sand is lost into La Jolla submarine canyon. This is enough sand to form a beach 100 feet wide, 5 feet deep, and over 2 miles long. Everts and Eldon (2005) estimate that approximately 1 million cubic yards of sand are lost into Mugu Submarine Canyon annually, while only an annual average of 1,000 cubic yards of sand are lost into Newport Submarine Canyon. These volumes span a large range and may not be representative of all canyons in California; however it is helpful to have an order of magnitude estimate for this component of a littoral cell. For the purpose of this study, the sand remaining at the end of a littoral cell, after all the sources and other sinks have been accounted for, will be directed to a submarine canyon where one exists and appears to be active.

Sand Mining (Sink): Sand and gravel are often removed from riverbeds, beaches, dunes or nearshore areas for construction and commercial purposes, representing a significant permanent sink for some of California's littoral cells. Overall in northern California, (i.e., from the Oregon border to the Russian River), about 8 million yds^3 of sand and gravel are removed each year from the coastal streambeds (Magoon and Lent, 2005). In southern California, the annual total is nearly 41 million yds^3, primarily in the greater Los Angeles and San Diego areas.

Sand mining has historically been a very large sink for beach sand that was difficult to quantify for the purposes of a sand budget. Due to the proprietary nature of sand mining, it is often challenging to gather information on specific mining practices for a given river or beach within a littoral cell. Information on mining is included in the sand budgets for this report only where available. Beach sand mining was terminated along the coast of California by the late 1980's to early 1990's in all areas except for the town of Marina in southern Monterey Bay where mining of the back beach is still occurring.

Harbor Dredging (check point): California's four large harbors and 21 small craft harbors (Figure 1.2) serve as constraints, or check points, when developing sand budgets. Half of the littoral cells in California (10 of the 20 cells delineated by Habel and Armstrong, 1978; Figure 1.4) contain at least one harbor that serves as an efficient littoral trap. Sand moving along the coast in the form of littoral drift is caught in the harbor entrance or trapping area, dredged, and typically, with a few exceptions, disposed of downdrift. The jetty and breakwater configuration and geometry of some harbors (e.g. Ventura and Channel Islands harbors) were built to trap sand before it enters the harbors' navigation channel. Sand is stored in these sediment traps until it is dredged, typically once or twice a year. Other harbors (e.g. Humboldt Bay, Oceanside, and Santa Cruz harbors) were not designed with a specific sediment trapping area; thus, once the fillet of sand upcoast of the first jetty reaches its maximum capacity, littoral drift travels around the arm of the jetty and accumulates in the harbor entrance, often forming a sandbar. While a minor amount of bypassing may occur, especially for those harbors that were designed without a specific trapping area, harbor dredging records are the most robust numbers we have for determining long-term annual gross and, occasionally, net littoral drift rates. When developing a sand budget for a littoral cell, you must have enough sand coming into the system from littoral drift, streams, seacliff erosion, or beach erosion updrift of the harbor to balance the average dredged volume. Often times, a littoral cell will have more than one harbor, and thus, multiple check points for quantifying the sand budget and the transport rates for the cell—these cases are optimal for developing a reliable budget.

While long-term dredging volumes are available for many California's harbors, and while we feel that these numbers can prove very useful in the determination of littoral cell budgets, there are significant uncertainties and difficulties involved in their use. Inherent errors exist when using harbor entrance dredging volumes to estimate littoral drift as checkpoints in the development of littoral cell sand budgets. Errors involved in estimating dredging volumes include, but are not limited to, the type of equipment used to dredge, and the time frame of sand removal and placement. There can also be uncertainties involved in the pre-dredge conditions and the method used to determine the reported volume of sand dredged from a location.

At Oceanside harbor detailed studies indicate that littoral drift reverses seasonally, such that sand may enter from either upcoast or downcoast directions and can, therefore, be dredged and counted twice. Dredging volumes at Oceanside may, therefore, represent gross vs. net littoral drift. This difference between gross and net drift can be important where significant littoral drift reversal occurs and where the configuration of the harbor entrance allows littoral drift to enter from up and downcoast directions.

There are other harbors, Santa Barbara, for example, where the combination of breakwater configuration and the location of dredge intake and discharge points, eliminate the potential for sand to enter the harbor from downcoast. As a result, there is essentially only net littoral drift at this location. Significant natural bypassing of sand across or around the dredging area can also occur (e.g., again at Oceanside, where sand appears to have been transported offshore and formed a very large permanent bar) (Dolan, Castens, et al., 1987; Seymour and Castel, 1985).

It is believed, however, that the margin of error involved in using annual dredged sand volumes as indicators of littoral drift rates, is still significantly lower than the error associated with quantifying the annual volumes of most sand sources and sinks within littoral cells (such as the sand contribution from streams and cliff erosion and sand lost to submarine canyons). For most harbors, entrances or trapping areas form nearly complete littoral drift traps. Where long-term data exist, harbor dredging records provide useful and rational checkpoints for littoral cell sand budgets. In the discussion of each individual littoral cell that follows, an effort is made to evaluate the validity or usefulness of the dredging volumes as proxies for littoral drift rates.

Chapter 2

EUREKA LITTORAL CELL SAND BUDGET

The Eureka littoral cell, located in northern California, is approximately 40 miles long and is bounded by Trinidad Head (Figure 2.1; Figure 2.2), a prominent rocky headland, to the north, and False Cape (Figure 2.1; Figure 2.3) to the south. At approximately its midpoint, this cell is interrupted by Humboldt Bay (Figure 2.1; Figure 2.4). Maintenance dredging of Humboldt Bay's entrance channel and bar serves as a potential indicator of the net and/or gross rate of littoral transport of sand moving alongshore in this region. Dredging of the bay's entrance channel also serves as a check-point for developing a regional sand budget for the Eureka littoral cell.

PHYSICAL SETTING

A cool and moderate climate dominates this stretch of northern California as a result of the cool, southward flowing California current. This area receives a moderate rainfall of approximately 30 to 40 inches per year between November and March, and the summers are often foggy until August. The prevailing winds in this area are from the north and northwest with average velocities from 4 to 15 miles per hour (Costa and Glatzel, 2002).

Unlike the moderate climate, the wave conditions within the Eureka littoral cell can be extreme. In fact, the wave climate in the Pacific Northwest is the most severe in the continental United States with swells from both the South and North Pacific battering the coast almost continuously. Northwestern swell dominates the wave climate; however, the most severe wave conditions typically come from southwest seas.

HUMBOLDT BAY

Humboldt Bay (Figure 2.1; Figure 2.4), located between 40 and 41 degrees north latitude, is the only major harbor between Portland, Oregon and San Francisco, California. The bay is 14 miles long with widths varying between half a mile and four miles. The bay has a small watershed, only 223 square miles, with no major rivers draining directly into it. As such, the input of freshwater is small, and circulation within the unstratified marine water within the bay is tidally dominated. The tide within Humboldt Bay is mixed semi-diurnal with a mean range at the entrance of 4.97 feet and a diurnal range of 6.93 feet (Costa and Glatzel, 2002). Entering Humboldt Bay can be quite hazardous, especially during winter storms when wave shoaling and strong currents are common in the entrance channel.

Two narrow sand spits, from one-eighth- to one-mile in width, separate Humboldt Bay from the Pacific Ocean on both sides of the tidal inlet serving as the entrance to

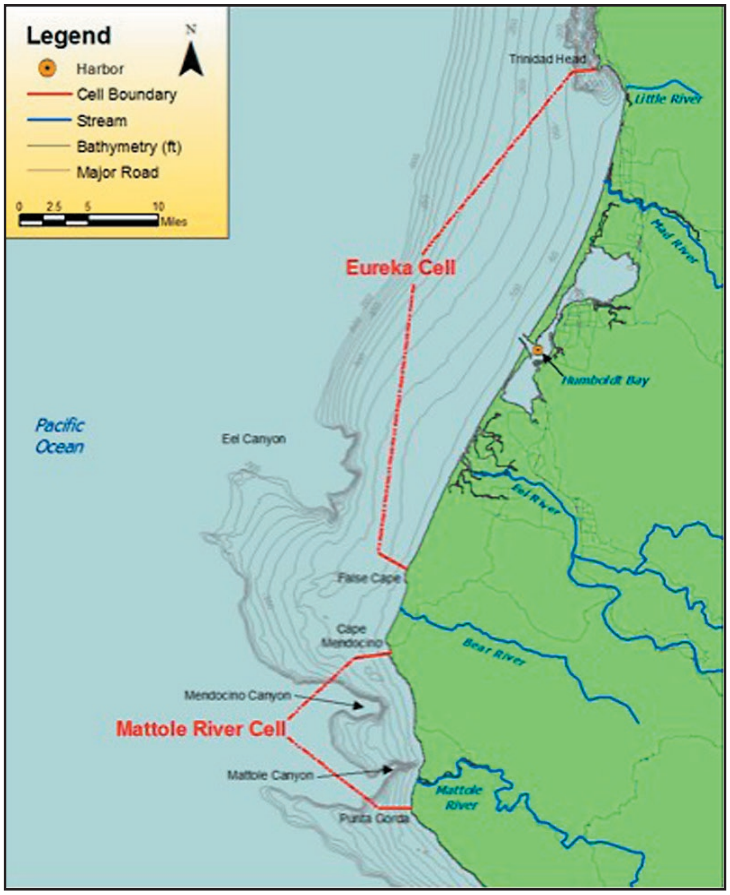

Fig 2.1: Location Map for the Eureka and Mattole littoral cells.

Fig 2.2: Trinidad Head, Copyright © 2002 Kenneth & Gabrielle Adelman

the bay. The north spit is relatively flat with low dunes near the southerly end rising gradually to the north into higher, heavily wooded sand dunes. Along an approximately three-mile stretch from the entrance of Humboldt Bay along the north spit, the shoreline has advanced seaward and varied as much as 3,400 feet adjacent to the north jetty to no change three miles north of the jetty since jetty construction (USACOE, 1973). In contrast to the wide north spit, the south spit is narrow, low, and mostly unvegetated and extends approximately four miles to Table Bluff, a high headland separating Humboldt Bay from the Eel River delta.

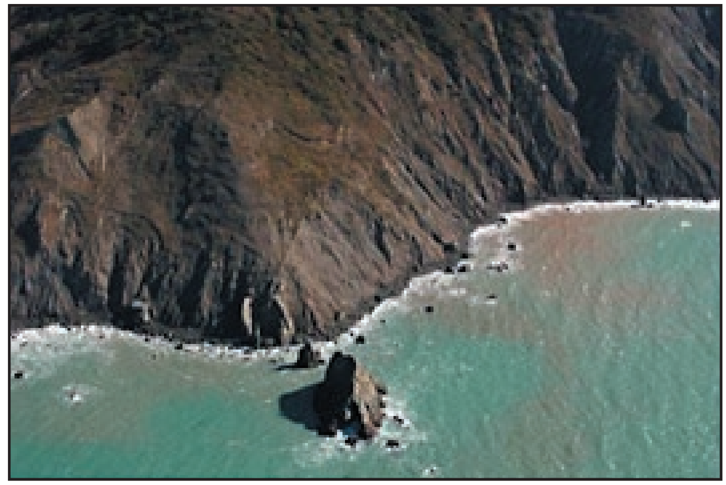

Fig 2.3: False Cape. Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 2.4: Humboldt Bay, 1971

Humboldt Bay consists of three basins: Entrance Bay, South Bay, and North (or Arcata) Bay. Entrance Bay is a dynamic feature located directly east of the entrance channel. Much of this shoreline is armored to protect against damage by waves propagating through the entrance channel. South Bay is just south of Entrance Bay, and is more of a constriction between two features than a defined channel. North Bay (or Arcata Bay) is connected to the entrance channel by a long, narrow, maintained channel called the North Bay Channel. North Bay splits off into two smaller channels, Samoa and Eureka channels.

Entrance Stabilization: Before the entrance to Humboldt Bay was stabilized, there was an 3,000 to 5,000 foot wide opening through the north and south sand spits forming a natural entrance with a bar located offshore in about 18 feet of water. In five-year cycles this inlet would migrate north to south along the length of the bay returning to the northern end once it reached the southern end (Noble, 1971).

Improvements to the interior of the harbor began in 1881; however, it wasn't until 1889 that the first attempt to stabilize the entrance to Humboldt Bay occurred. Due to the high-energy environment and the dynamic behavior of the spits, attempts to stabilize the entrance with jetties proved to be a challenging undertaking. Approval of the first engineering project, twin jetties, occurred in 1888, but the construction and heavy maintenance that was required for these jetties lasted until the early 1930's. Improvements and additional repair of the jetties were still required until the 1970's. Finally, in the late 1970's a more extreme engineering approach was undertaken. Massive artificial armor units, or dolos, were placed on the jetties to offer additional protection against the extreme wave conditions common in this area (Costa and Glatzel, 2002). Currently, two rubble mound jetties extending from the end of the two sand spits are in place to stabilize the inlet, or entrance channel. At their seaward end, 2,100 feet separate the 4,500 foot-long north jetty from the 5,100 foot-long south jetty.

Entrance Channel Maintenance Dredging: Originally, the bar and entrance channel to Humboldt Bay were dredged to a depth of 30 feet. In 1934, the channel was deepened to 35 feet in order to accommodate larger vessels, which required the removal of about 200,000 yds^3 of material (Noble, 1971). Subsequent to this deepening operation the bar became relatively stable. According to O'Brien's Ratio, the entrance channel depth for a harbor this size (with a tidal prism equal to 4.38 x 109 cubic feet) and a distance between the two stabilizing jetties of 2,100 feet is 35.2 feet (Noble, 1971); thus, the entrance channel was in equilibrium. This equilibrium was disrupted however in 1952 when the bar and entrance channel was deepened to 40 feet. Following this deepening, routine maintenance dredging has been required annually (Figure 2.5). Between 1955 and 2000, the long-term average volume of sand dredged from the bar and entrance channel was ~465,000 yds^3/yr. The last alteration of the entrance channel occurred in 1999, when the 40-foot channel was deepened to 48 feet (Winkelman et al., 1999).

Dredge Disposal: Between the 1940's and 1988, dredged material was deposited southwest of the south jetty in 60 to 90 feet of water in a disposal site named SDF3 (Kendall et al., 1991). Heavy use of this disposal site decreased the water depth in this location to 40 feet causing waves to shoal and break and the area to become a navigational concern. As a result, SDF3 was abandoned in 1988.

Between 1988 and 1989 a temporary disposal site, NDS,

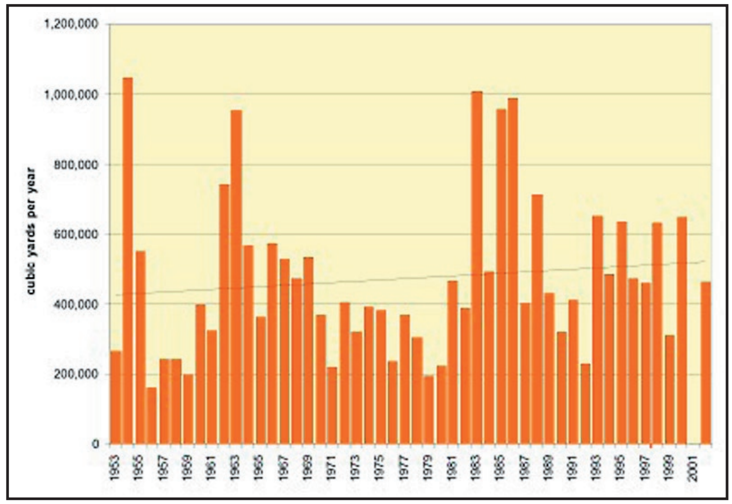

Fig 2.5: Dredging volumes for Humboldt Bay's bar and entrance channel from 1953-2000

was used, which was also located south of the jetty in 56 feet of water; this site was ultimately terminated (Kendall et al., 1991). Since 1990, dredged material has been taken offshore to the Humboldt Open Ocean Disposal Site (HOODS), which is located three miles offshore in 180 feet of water. At this depth, the sand is effectively removed from the littoral system (Winkelman et al., 1999). It is estimated that annual dredging removes ~25% of the sand from the littoral system in this cell (Kendall et al., 1991; Winkelman et al., 1999).

BEACHES

The shoreline in this cell is comprised of beaches backed by large dunes from the Little River to the entrance of Humboldt Bay, continuing down-coast with narrow beaches to just north of False Cape. Around the False Cape area and southward, sandy beaches are nonexistent and the coast becomes very rocky (Figure 2.3). Where they exist, the beaches tend to be wide and flat composed of fine to medium-grained sand (USACOE, 1973). Glogoczowski and Wilde (1971) found that the littoral cut-off diameter (the diameter which less than 1% of the sand on the beaches is finer than) for beaches in this cell is 0.125mm.

DUNES

Sand dunes along the north and south spit of Humboldt Bay serve as both sources and sinks of beach sand in the Eureka littoral cell. Extensive dune fields exist between the Little River to the north and the Eel River to the south with an interruption in this field at the entrance to Humboldt Bay. Between the Little and Mad rivers there is a narrow dune field that has been described by Cooper (1967) as having two distinct ridges. The outer dune ridge is approximately 20 ft above the high tide and is covered mostly by pioneer vegetation. The inner, more substantial ridge reaches a maximum height of 50 ft and is more densely vegetated with portions of the dune remaining active and unvegetated. The dunes extend for eight miles south of the Mad River and are massive with the height of dune crests reaching 35 to 45 ft (Cooper, 1967). On the south spit, the dunes are narrow, low, and sparsely vegetated.

An extensive monitoring project of the beaches and dunes on the north and south spit was undertaken by Winkelman, et al (1999) analyzing changes in sand volume on the beaches and dunes from 1992-1998 using digital terrain maps (DTMs) in a Geographical Information System (GIS). During this 6-year period the south spit's subaerial beach and dune system gained a total of 1.6 million cubic yards of sand, or ~270,000 yds^3/yr (Winkelman et al., 1999). The dune line along the south spit remained stationary or moved seaward during the course of the study. The majority of the beaches and dunes along the north spit, however, decreased in both volume and width, losing a total of 1.05 million yds^3, or ~175,000 yds^3/yr over the 6-year period (Winkelman et al., 1999).

LITTLE RIVER

The Little River (Figure 2.1; Figure 2.6), located four miles south of Trinidad Head and eight miles north of the Mad River mouth, is the northernmost source of sand for the Eureka littoral cell. Between Trinidad Head and Little River, the beaches are narrow to nonexistent. South of the river mouth the beaches become wider and begin to be backed by extensive dune fields. The Little River has a total drainage area of 40.5 square miles, and currently no dams or diversions on this river exist. The present annual sand flux (sediment coarser than 0.0625 mm) from the Little River is ~53,000 yds^3/yr. This is an over-estimation of the sand input to the regional sand budget in this cell, however, because the finest sand that will remain on the beaches and will not be carried offshore (the littoral-cut-off diameter) is 0.125 mm (Glogoczowski and Wilde, 1971). Little River, however, does not have a detailed grain-size analysis of the sediment load, which could allow for a more accurate calculation of the sand supplied to the beaches by this river.

Fig 2.6: Mouth of the Little River. Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 2.7: Mouth of the Mad River. Copyright © 2002 Kenneth & Gabrielle Adelman

MAD RIVER

The Mad River (Figure 2.1; Figure 2.7) is located 11 miles south of Trinidad Head and 13 miles north of the entrance to Humboldt Bay. This river has a drainage area of approximately 494 square miles. For most of its reach, the Mad River flows through a steep canyon. Upon entering the Blue Lake area, the valley becomes wider and the river emerges onto a relatively flat flood plain. Humboldt Bay was once an estuary of the Mad River; today the river only spills into the bay during major flood events.

Two dams have been built on the Mad River: Ruth Dam and Sweasy Dam. Ruth Dam is located east of Forest Glen with the reservoir having a total capacity of 48,000 acre-feet. Water is released down the Mad River for municipal use. Sweasy Dam, constructed in 1938, impounded a 3,000 acre-feet reservoir.

	Natural Discharge (yd^3/yr > 0.0625mm)	Post-Dam Discharge (yd^3/yr > 0.0625mm)	Reduction (yd^3/yr)	Reduction (Percent)
Little River	53,207	53,207	0	0
Mad River	752,072	687,340	64,732	9%
Eel River	3,793,057	3,753,105	39,951	1%
Total	4,598,336	4,493,653	104,683	2%

Table 2.1: Sand Reduction by Dams (Willis 2003)

It ultimately filled with sediment and was removed by dynamiting in August of 1970. A third dam, Butler Dam, was proposed at a site located about half-a-mile downstream from the north end of the valley that would have provided 460,000 acre-feet of storage, but this dam was never constructed. The present annual sand flux (sediment coarser than 0.0625 mm) from the Mad River is ~690,000 yds^3/yr; this is a reduction of 9% (Table 2.1) from the natural sand flux due to the damming of this river (Willis and Griggs, 2003; Willis et al., 2002). Using the littoral-cut-off diameter for this cell of 0.125 mm, the Mad River contributes ~486,000 yds^3/yr of sand that is coarse enough to remain on the beaches.

EEL RIVER

The Eel River (Figure 2.1; Figure 2.8) discharges, on average, more suspended sediment than any river in the lower 48 states after the Mississippi (Meade and Parker, 1984), and has the highest recorded average annual suspended sediment yield of any river its size in the United States (Brown and Ritter, 1971). The Eel River basin has one of the largest sediment yields per unit area in the world (Brown and Ritter, 1971; Hole-man, 1968; Judson et al., 1964). In addition, this river has the longest continuous record of water and sediment discharge in California.

Willis (2003) compiled all current USGS water and sediment data through the 2000 water year at the USGS gauging station at Scotia located ~21 miles from the coast. According to these data, the annual sediment load is highly variable for the Eel River ranging from ~130 million yds^3 of sediment in the 1965 water year to 15,500 yds3 in 1977. Currently two major dams, the Scott and Van Arsdale dams impound the flow of the Eel River. Both dams are located on the upper portion of the Eel River and together impound more than 344 square miles (11%) of the basin. Van Arsdale Dam, the lower of the two, functions as a diversion dam facilitating Pacific Gas and Electric's (PG&E) Potter Valley project for hydroelectric power generation and irrigation in the Russian river basin.

The diversion has not significantly reduced the flows at Scotia that transport the bulk of sediment, and as such does not significantly affect sediment transport. In contrast, Scott Dam impounds Lake Pillsbury, an 80,000 acre-ft reservoir, and impacts flows on the Eel River. According to Willis (2003) the annual sand discharge (coarser than 0.0625 mm) averaged over 89 years (from 1911-2000) is 4.9 million tons or 3.6 million yds^3 of sand annually when a mean bulk density of 1.35 tons/cubic yard is assumed; however the yearly sand discharge ranges from nearly 35.5 million yds^3 in 1965 to 4,200 yds^3 in 1977. Sand-sized material (coarser than 0.0625 mm) constitutes ~25% of the sediment yield and bed load was taken to be ~4% of the total load (Hawley and Jones, 1969; Willis and Griggs, 2003). The long-term annual sand discharge (3.6 million cubic yards of sand) is consistent with that found by Ritter (1972) and Griggs (1987a) of 2.9 million cubic yards and 3.3 million cubic yards respectively.

In addition, sand from the Van Duzen River, a tributary to the Eel River, adds an estimated 179,000 cubic yards of sand each year (Brown and Ritter, 1971; Willis et al., 2002). The combined impact of the Scott and Van Arsdale dams, which impound 11% of the Eel River basin, only reduces the sand discharged by the Eel River by 1.1% (Willis and Griggs, 2003).

Fig 2.8: Mouth of the Eel River. Copyright © 2002 Kenneth & Gabrielle Adelman

In terms of a sand budget, it is important to consider the sediment that will actually remain on the beach and be carried alongshore as littoral drift–sand that is coarser than the littoral-cut-off diameter of 0.125mm. The Eel River contributes ~2.3 million cubic yards of beach-size sand annually.

DEPOSITION OF SAND SUPPLIED BY THE EEL RIVER

Where in the littoral system the 2.3 million cubic yards of beach sand discharged on average annually by the Eel River ends up is a debatable issue. The lack of sandy beaches south of the Eel River and the minimal sand accumulation against Humboldt Bay's south jetty north of the Eel River offer few clues as to the direction of transport. As discussed in the subsequent section concerning littoral drift direction, it is unclear whether this sand moves north or south, and it seems quite evident that although the Eel River is the main contributor of sand to this cell, most of the sand is not ending up on the beaches. Ritter (1972) proposed three sinks for this sand: 1. Deposition in the estuary at the mouth of the Eel River; 2. Deposition on the continental margin and loss into the Eel Canyon; and 3. Deposition on the nearby beaches.

Near the mouth of the Eel River, which is tidal for about four miles inland (Evenson, 1959), several islands, channels, and sloughs show evidence of deposition in the estuary (Shepard and Wanless, 1971). Using a surface area for the estuary at high water of 2.6 square miles (Johnson, 1972) and an average long-term sand load of 2.3 million yds^3/yr, the estuary would be infilling at an average rate of 1.3 feet per year. This rapid rate of deposition is not observed. Although the actual rates of deposition are unknown, it seems highly improbable that this is a major sink for sand emanating from the Eel River. It is concluded that most of the sand transported by the Eel River makes it to the ocean, passing through the estuary without much deposition.

To determine if sand was being deposited along the continental margin, Ritter (1972) studied the bottom contours off the mouth of the Eel River. He determined that "although the 30- and 60-foot contours parallel the shoreline, the contours from 120 to 240 feet show a convex bulge." Ritter (1972) used this as evidence that much of the sediment discharged from the Eel River is spread over the continental margin as a blanket deposit or submarine fan. Nittrouer (1999) also concluded that sand accumulates on the inner shelf (<180 feet water depth) offshore of the Eel River. A model developed by Morehead and Syvitski (1999) indicates that under modern geologic conditions, the majority of deposition for sediment discharged from the Eel River occurs up to 12 miles north of the river mouth and is confined to within 6 miles of the coastline.

Submarine canyons located close to shore along the California coast often serve as major sinks for littoral sand. Although Eel Canyon, reaching to within seven miles of the mouth of the Eel River, is located a considerable distance from the shore, it may serve as a sink for sand discharged from the Eel River. As with many issues in this littoral cell however, this is still highly debated. Silver (1971) concluded that the submarine alluvial fan at the mouth of the canyon is far too small considering the large sediment loads that theoretically would be making their way down the canyon. However, by interpreting seismic records, Greene and Conrey (1966) discovered a buried canyon extending shoreward from the present-day canyon, and concluded that sediment deposited by the Eel River must have filled this shoreward part of the canyon and now the sediment is filling the head of the present canyon. More research is needed to determine if Eel Canyon serves as a major sink for sand (coarser than 0.125mm) discharged by the Eel River.

If the sand discharged from the Eel River is not filling the estuary, and it is not ending up in the Eel Canyon or on the continental margin, than the only other logical place it could be is on the beaches along the coast north and south of the Eel River mouth, or perhaps deposited in Humboldt Bay. The beaches north of the river are quite narrow, and the beaches south of the river are non-existent except for the occasional pocket beach. These small beaches are not what would be expected around the mouth of a river discharging an average of over 2 million cubic yards of beach-sand-sized sediment annually.

Ritter (1972) collected sand samples along the entire littoral cell, from Trinidad Head to Centerville Beach, and performed a grain-size and mineral analysis to determine the source of sand. He determined that mean grain size became finer as the distance from the mouth of the Eel River increased. Ritter (1972) supported a southward littoral drift, and his grain size statistics demonstrated a significant difference between mean grain sizes north and south of the entrance to Humboldt Bay, indicating different source material. Ritter (1972) concluded that sand north of Humboldt Bay is supplied by the Mad and Little rivers and sand south of Humboldt Bay is supplied by the Eel River. This conclusion was consistent with his heavy mineral analysis. Ritter (1972) could not explain, however, why the beaches between Humboldt Bay and False Cape are so small and narrow with a supply of sand as great as the Eel's. It is not likely that Humboldt Bay is a significant sink for the sand discharged from the Eel either due to the theoretical rate of infilling that would result from such a large sand load (Ritter, 1972).

DIRECTION OF LITTORAL DRIFT OR LONGSHORE TRANSPORT

Understanding the predominant direction of sand movement, or the direction of littoral drift, is an essential component in the development of a robust regional sand budget. In the Eureka littoral cell, the direction of longshore transport is still a contentious issue, and one that has not been fully resolved. Ideally, the northerly and southerly movement of sand can be assessed to provide both net and gross longshore transport rates; however, in the Eureka cell there has been no confident assessment made for the quantities of sand involved in this movement.

The most notable study on the direction of littoral drift in this area was done by Noble (1971) using unpublished U.S. Army Corps of Engineers reports focusing on the construction of the Humboldt Bay jetties and the resulting impact to the shoreline. Noble argues for a dominant north to south transport, stating that the natural condition of Humboldt Bay's entrance inlet, before the jetties were emplaced, cycled from north to south over a five-year interval. Over the five-year cycle the inlet would migrate 1.5 miles from north to south only to open again at the northern end and repeat the cycle. Additionally, the waves along this stretch of coast are predominantly from WNW and to the north of WNW, which will produce a southerly drift; thus, this evidence indicates a predominant direction of drift to the south (Noble 1971). Following the initial phase of construction of the Humboldt jetties (1870 to 1899), the shoreline advanced along both the north and south spits; the north spit shifting seaward 2,600 ft and the south spit shifting seaward 2,200 ft. Noble cited this as additional evidence for a north to south drift. He also noted that the Army Corps of Engineers estimated the net longshore transport in the vicinity of Humboldt Bay to be on the order of 500,000 yds^3/yr to the south. Habel and Armstrong (1978) also indicate net transport to be to the south in this cell; however, they do not give any evidence in support of their conclusion.

Borgeld et al. (1993) believe that Noble (1971) was incorrect in his assessment of the evidence supporting a north to south transport, and instead proposed that the dominant transport direction is from south to north. By assessing the bar and channel configuration of Humboldt Bay they suggest a south to north transport both prior to and following jetty construction. Additional indication of a south to north transport direction is given by the fact that between completion of the jetties in 1899 until 1903, a time during which no maintenance of the jetties was undertaken, allowing for the ends of the jetties to severely deteriorate and fall below mean lower low water, the south spit adjacent to the jetty advanced seaward by 1,000 ft and the north spit eroded. However, by 1912, the south spit had eroded 800 ft and the north spit was continuing to retreat. Reconstruction of the Humboldt jetties occurred between 1912 and 1916. During this time, the north spit once again advanced seaward 2,300 ft while the south spit advanced seaward by only 450 ft. Once again, Noble (1971) saw this as evidence for a dominant north to south littoral drift. Borgeld et al (1993) however, do not agree with this interpretation and maintain that the drift is from the south to north.

Also of notable interest in the debate on transport direction, is the longshore sorting of sand on the beaches. Snow (1962) found that the mean grain size of sand on the beaches decreased from south to north, once again indicating a south to north transport direction. However, as discussed earlier, Ritter (1972) concluded that mean grain size and heavy mineral tracers such as garnet indicate that the Eel River is the main contributor to the beaches in the southern end of the cell, while the Mad and Little river are the main sources of sand to the beaches north of Humboldt Bay, thus arguing a dominant north to south transport in the northern reach of the cell (from Trinidad head to the Humboldt Bay), and a south to north littoral drift in the southern reach of the cell (from False Cape to Humboldt Bay). However, Bodin (1982) found that there was a systematic south to north decrease in the mean grain size of the beach sand throughout the full length of the cell, and his heavy mineral analysis concluded that Eel River sand was the primary source of sand throughout the cell indicating a dominant south to north transport direction throughout the Eureka Cell.

The Eel River, located in the southern portion of the cell, contributes most (77%) of the sand to the Eureka Cell. Significantly smaller volumes of sand are provided by the Mad and Little rivers, which are both located in the northern region of the cell. Borgeld et al. (1993) argue that this fact alone, the extremely large volume of sand emanating from the Eel River, is evidence for a south to north transport. However, if such a large volume of sand is discharged from the Eel River and travels north, it would be expected that the south spit of Humboldt Bay would be accreting significantly next to the southern jetty and be offset a great deal more seaward than the north spit; this is not the case, however.

If a southward transport direction is supported, one would expect wide sandy beaches south of the Eel River. However, there are no sandy beaches in this area, nor is sand accumulating on the north side of False Cape, the proposed terminus of the Eureka littoral cell. There are also no submarine canyons between Eel River and False Cape reaching close enough to shore to serve as a sink for the sand. One possibility is that False Cape is not acting as a complete barrier to littoral transport. Sand may be making its way around False Cape, continuing along the shoreline around Cape Mendocino, and ultimately end up flowing into the Mendocino and Mattole canyons. This theory would require that the long accepted southern boundary for the Eureka littoral cell, False Cape, needs to be extended southward to include Mendocino and Mattole canyons.

Overall, the issue concerning the direction of longshore drift in the Eureka Cell is unresolved. Convincing evidence is presented for both a north to south transport as well as a south to north transport. In this cell, what may be more important to realize when developing a regional sand budget than the dominant direction of littoral drift, or considering alterations to the coastline, is that the quantities and direction of littoral drift in this cell may change from year to year, and engineering activities along the coastline may have far reaching consequences. In the most recent studies, sand transport in the Eureka Cell is characterized by a large gross movement with a small net movement of sand to the north (Madalon and Kendall, 1993; Winkelman et al., 1999).

The sand budget developed for this cell should be used with caution because of the inconclusive nature of the transport direction studies. After assessing the literature concerning the longshore transport direction, the evidence appears to be stronger in supporting a dominant north to south transport direction north of Humboldt Bay, and a bidirectional transport direction south of Humboldt Bay.

DISCUSSION

Development of a regional sand budget for the Eureka Cell is challenging due to the uncertain direction of littoral drift and the undefined sink for the extremely large volume of sand discharged annually from the Eel River. What is known is that the Little and Mad rivers contribute ~53,000 and ~486,000 cubic yards of beach-size (>0.125 mm) material annually north of Humboldt Bay. Eighty-nine percent of the total sand discharge from these river occurs between December and February (DeGraca and Ecker, 1974), making most of this beach compatible material available within a very short time, thus exceeding potential littoral transport and producing a surplus of sand north of Humboldt Bay. As a result, extensive sand dunes exist north of the bay. It has been estimated by the Army Corps of Engineers that the net littoral drift for this cell in the vicinity of Humboldt Bay is ~500,000 cubic yards of sand annually (Noble, 1971). This volume is consistent with the long-term average

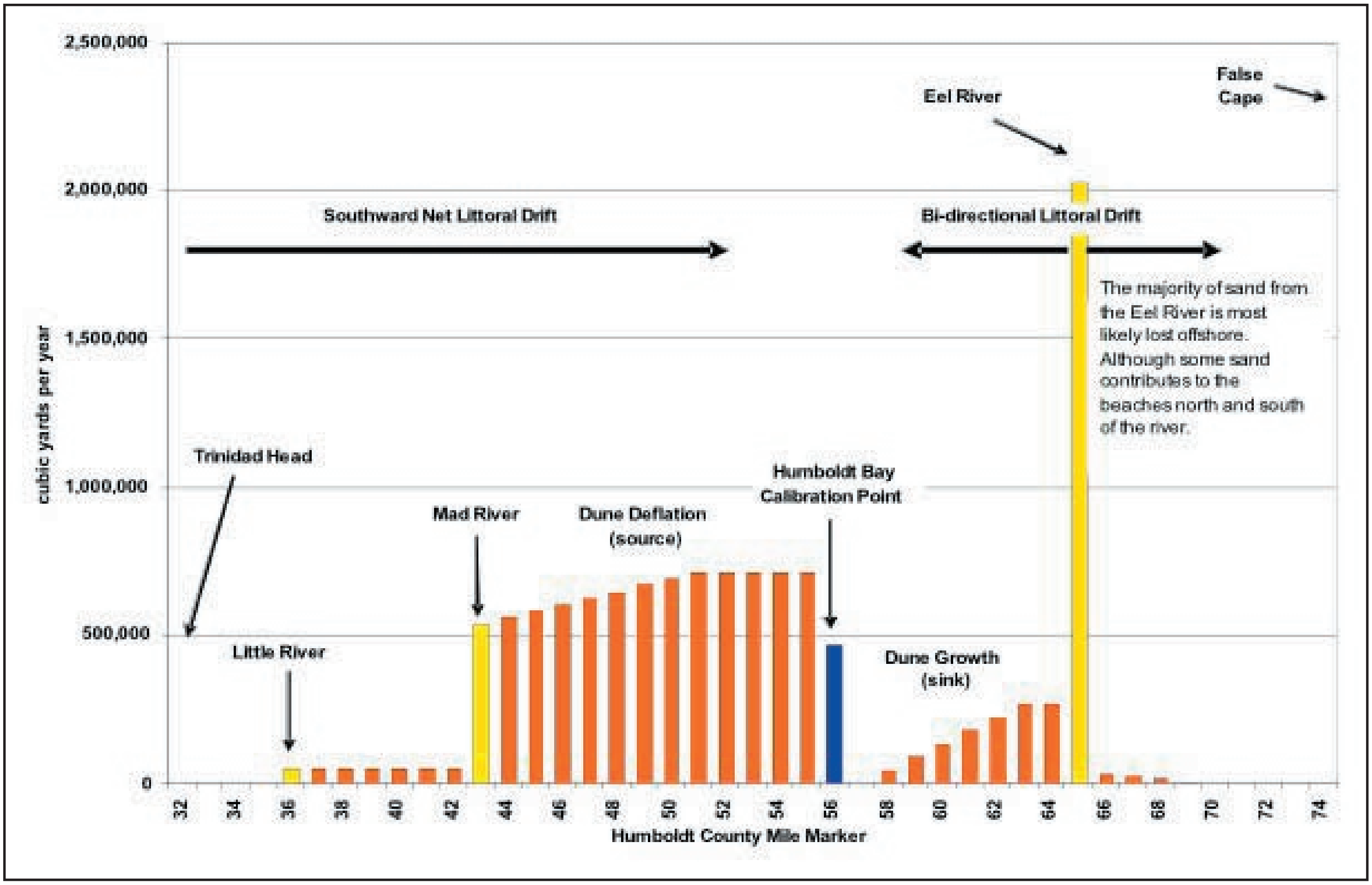

Fig 2.9: Running, mile-by-mile sand budget for the Eureka littoral cell

annual entrance channel and bar dredging for Humboldt Bay (~465,000 cubic yards annually).

It is not clearly understood why the sand on the beaches around the mouth of the Eel River is so sparse considering it is discharging ~2,300,000 yds^3/yr. The sand supply from the Eel River should make the surrounding beaches wider and the dunes higher. However, the beaches north of the mouth are narrow and the dune sizes do not reflect an extremely large supply of sand. Beaches south of the mouth are practically nonexistent, narrow, pocket beaches. The dimensions of the estuary around

Sources	Cubic Yards per Year
Little River	53,000
Mad River	486,000
Eel River	2,300,000
Dunes	175,000
Total	3,014,000
Sinks	Cubic Yards per Year
Dunes	270,000
Humboldt Bay (offshore)	465,000
Offshore Losses (estimated in order to balance the sand budget)	2,279,000
Total	3,014,000

Table 2.2: Sources and Sinks for the Eureka Littoral Cell

the Eel River and Humboldt Bay are not large enough to accommodate the heavy sand load from the Eel without rapidly infilling, and Eel canyon appears to be located too far offshore to serve as an adequate sink for littoral-sized sand. Ritter (1972) concludes that "the Eel River, although undoubtedly contributing sand to all the places mentioned above, clearly deposits most of its sand load on the continental shelf." This conclusion is consistent with findings by Nittrouer (1999) and Morehead and Syvitski (1999). An additional possibility is that littoral drift moving south is deflected offshore into deeper water, makes its way around Cape Mendocino, and is eventually lost to Mattole and Mendocino submarine canyons; this theory would necessitate changing the southern boundary of the Eureka Cell. Based on grain size analyses and mineralogy (Bodin, 1982; Ritter, 1972; Snow, 1962), the Eel River is thought to be the chief contributor of sand to the beaches between Humboldt Bay and its mouth.

CONCLUSION

In order to create a definitive sand budget for the Eureka Littoral Cell, more research will need to be completed to determine the littoral transport direction(s) for the cell and the sinks for sand discharged from the Eel River. A detailed multibeam bathymetric study from the shoreline to the head of Eel Canyon is highly recommended and may help resolve the uncertainties and debates. With the current state of knowledge, it is assumed that the ~540,000 yds^3 of sand discharged by the combined Mad and Little rivers travels south as littoral drift, gains and loses sand from the immense dune fields on the north spit, and is eventually deposited in the bar and entrance channel to Humboldt Bay, where ~465,000 yds^3 of sand is dredged annually and deposited offshore, effectively removing it from the littoral system (Figure 2.9; Table 2.2). South of Humboldt Bay, ~2,300,000 yds^3 of sand is discharged annually from the Eel River, the majority of which is lost offshore along the continental shelf or deposited into Eel Canyon. Some of this sand travels north to feed the beaches along the south spit between the mouth of the Eel River and Humboldt Bay, and some of the sand travels south along the rugged coast to False Cape (Figure 2.9; Table 2.2). Sand from the Eel River may in fact make its way around Cape Mendocino with an eventual sink at Mendocino and Mattole submarine canyons.

Chapter 3

SANTA CRUZ LITTORAL CELL SAND BUDGET

The Santa Cruz littoral cell (Figure 3.1) extends, for the purpose of this study, approximately 75 miles from Pillar Point to the Monterey Submarine Canyon at Moss Landing in central Monterey Bay (Griggs, 1987b; Limber, 2005; Perg et al., 2003; Weber et al., 1979; Yancey and Lee, 1972). This stretch of coast is morphologically diverse with broad continuous marine terraces fronted by beaches in Monterey Bay and Half Moon Bay. North of Monterey Bay, resistant headlands punctuate the coastline creating pocket beaches.

The Santa Cruz littoral cell has a Mediterranean climate moderated by the California Current. The Santa Cruz Mountains, backing nearly the entire coastline, have pronounced orographic effects on the climate in the region with 90% of the annual precipitation occurring between the months of November and March (Rantz, 1971). The average yearly rainfall is ~31 inches near Santa Cruz and decreases to ~22 inches in the northern portion of the cell (Rantz, 1971).

PHYSICAL SETTING

Pillar Point to Año Nuevo: Pillar Point appears to be the northern boundary of the Santa Cruz littoral cell (Figure 3.1). It is believed that little to no sand is transported around Point San Pedro (Limber, 2005). As evidence of the cell boundary, Half Moon Bay Harbor, located just south of Pillar Point (Figures 3.1 and 3.2) has never required maintenance dredging as a result of sediment entering the channel entrance, nor is there a significant build-up of sand against the breakwater. There is, however, a considerable amount of sand immediately south of Half Moon Bay, indicating sand may be leaking into the cell from upcoast. Seafloor rock outcrops off of Pillar Point, responsible for creating large waves at the popular big-wave surf spot, Mavericks, may steer sand around the harbor to the downcoast shore. For the purpose of this study, Pillar Point will be used as the northern boundary for the Santa Cruz littoral cell, however, this boundary may not be definitive; sand may leak into the cell from north of Pillar Point.

Half Moon Bay, located between Pillar Point to the north (Figure 3.2) and Miramontes Point to the south, is a 6.5-mile long, hook-shaped bay consisting of sandy beaches backed by low, eroding bluffs. In 1959, a long breakwater was constructed across the northern portion of Half Moon Bay to create a protected harbor. Construction of this breakwater caused a change in wave refraction in the bay and resulted in the increased erosion (from 3 inches per year to as high as 80 inches per year) of the low, weak bluffs at the eastern end of the breakwater (Griggs et al., 2005).

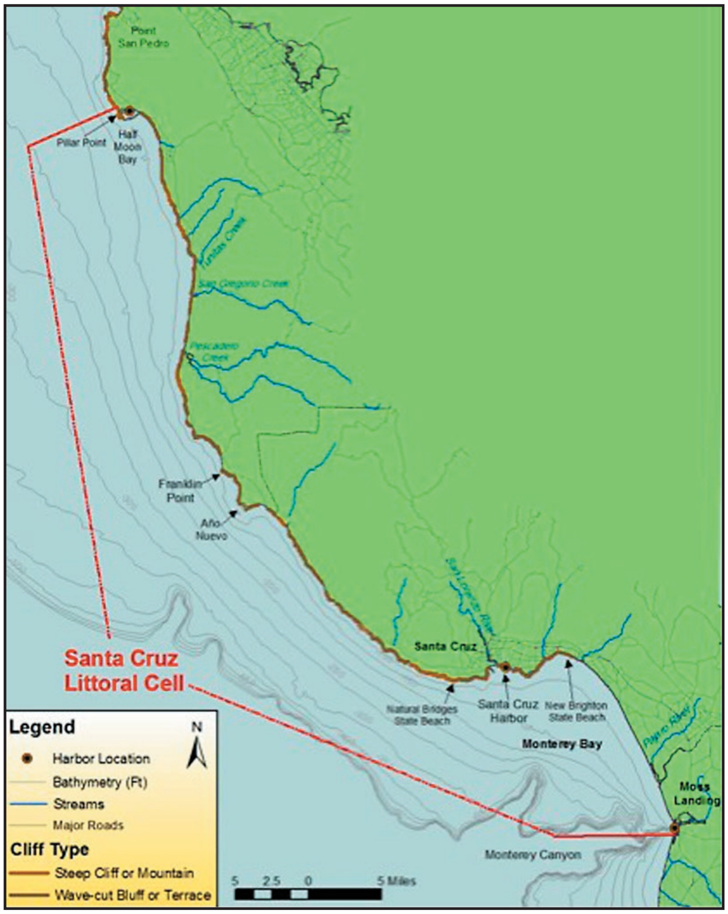

Fig 3.1: The Santa Cruz littoral cell

South of Miramontes Point, the ~6 mile coastline to Tunitas Creek (Figure 3.3) consists of steep, irregular cliffs ranging from 70- to 160-feet high fronted by narrow and/or pocket beaches. While the rates of seacliff erosion in this vicinity are quite variable, the majority of these cliffs are relatively stable (Griggs et al., 2005).

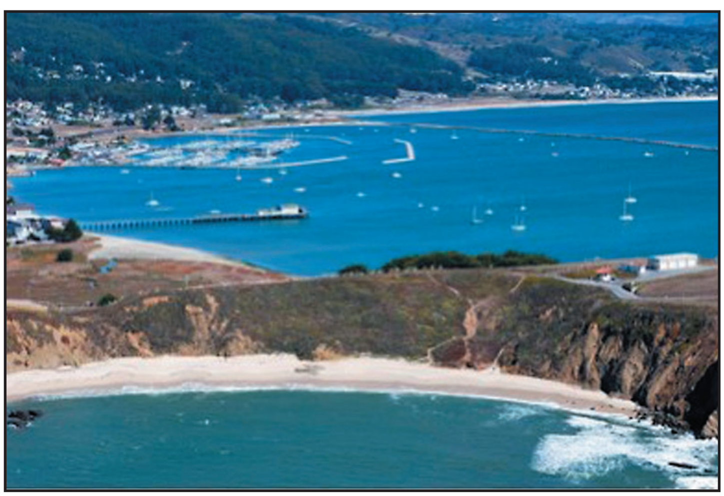

Fig 3.2: View west from Maverick's, showing the tail-end of Pillar Point and Half Moon Bay Harbor, California. Copyright © 2004 Kenneth & Gabrielle Adelman

From Tunitas Creek (Figure 3.3) south to Pescadero Creek (Figure 3.4), the coastline consists of sandstone and mudstone coastal cliffs interrupted by coastal streams. Narrow, sandy beaches often front these

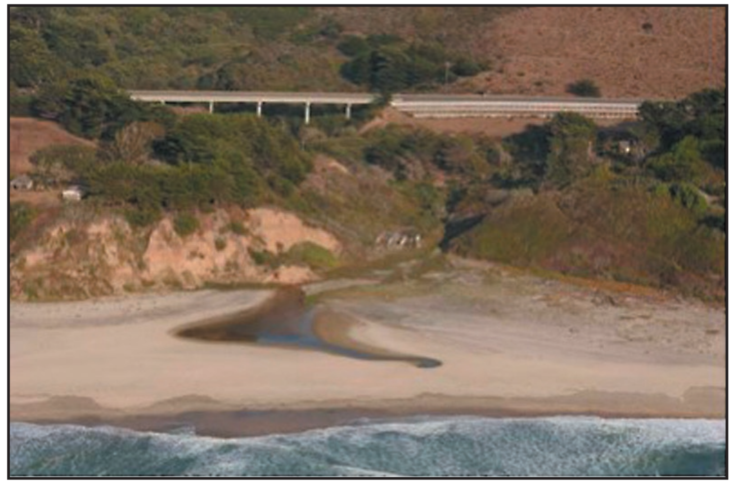

Fig 3.3: Tunitas Creek. Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 3.4: Pescadero Creek. Copyright © 2002 Kenneth & Gabrielle Adelman

relatively stable seacliffs during the summer months.

Low, rocky cliffs and bluffs with small pocket beaches mark the coastline from Pescadero Creek to Franklin Point (Figure 3.1). Resistant sandstones, mudstones and conglomerates are exposed to wave erosion along this stretch of coast. Stabilized sand dunes characterize Franklin Point. Seacliff erosion along this stretch of coast is minor because of the resistance of the rocks to wave attack (Griggs et al., 2005).

Point Año Nuevo is a low-lying headland near the southern boundary of San Mateo County (Figure 3.1). The nearly flat, broad marine terrace exposed at this point is comprised of a resistant sandstone and mudstone bedrock overlain by a 5- to 30-feet thick layer of easily eroded sand, gravel, and silt (Griggs et al., 2005). On its seaward half, this headland, or point, is topped by a 5,000-to 6,000-year-old dune field that has been stabilized and vegetated over the past 110 years (Griggs et al., 2005). The northern portion of the shoreline at Point Año Nuevo is nearly linear with sand and gravel beaches backed by low bluffs. The southwest-facing shoreline is essentially a curved, pocket beach formed between two rocky points, while the southern portion of the point consists of irregular, low vertical- to overhanging-cliffs.

Año Nuevo Island, lying 2,300 feet offshore from the southern point of the headland, probably formed in the time between the late seventeenth to mid-eighteenth century (Griggs et al., 2005; Seals, 2005). When first discovered in 1603, the Año Nuevo area was named Point Año Nuevo and was presumably a peninsula. Continued sea level rise and coastal erosion, possibly in connection with movement related to prehistoric earthquakes along the San Gregorio Fault Zone, eventually led to the formation of an island separated from the mainland by a channel (Griggs et al., 2005).

Point Año Nuevo once formed a barrier, or trap, for sand traveling south as littoral drift, which impounded sand and formed wide, sandy beaches north of the point. Littoral sand blew up onto the low marine terrace and moved across the point as dunes, eventually cascading over the southern portion of the headland where it once again entered the littoral cell. Once Año Nuevo Island separated from the mainland, the point was no longer an effective littoral barrier; thus, the wide, sandy beach supplying the dunes disappeared on the north side of the headland. The formation of the channel resulted in as much as 12 to 18 million yds^3 of sand that had previously been trapped by the headland, to again enter the sand budget over the past 200 to 330 years (Griggs et al., 2005). Tens of thousands of cubic yards were added to the sand budget annually from this reserve of sand. However, the large source of sand is now depleted. As the end of the wave of extra sand migrates down the coast, beaches in this littoral cell, south of Point Año Nuevo may return to a natural, narrower width (Griggs et al., 2005).

Año Nuevo to Natural Bridges State Park: From Año Nuevo to Natural Bridges State Park (Figure 3.1) the coastline is predominantly undeveloped. Agricultural fields are situated atop the lowest and youngest of a sequence of up to five marine terraces (Figure 3.5). The seacliffs along this stretch of coast range from 30- to 200-feet high and consist of moderately resistant mudstone. Beaches exist where coastal streams have incised the marine terrace to reach the ocean. Average long-term seacliff erosion rates in this vicinity are relatively low (3 to 6 in/yr or less) due to the resistance of the Santa Cruz Mudstone to wave attack and the protection offered by low mudstone benches, or shore platforms, commonly extending seaward at the base of the cliffs (Griggs et al., 2005).

Natural Bridges to New Brighton State Beach: From Natural Bridges State Park to New Brighton Beach (Figure 3.1) the coastline is almost continuously developed. This 10-mile stretch of coast consists off narrow to wide beaches backed by seacliffs ranging from 25- to 75-feet-high. Wider beaches exist at stream mouths and north of natural and artificial retention structures such

Fig 3.5: Marine terrace at Sand Hill Bluff located just north of Santa Cruz Copyright © 2002 Kenneth & Gabrielle Adelman

as headlands, jetties and groins. As you move from west to east along this stretch of coast, the more resistant Santa Cruz Mudstone dips below the younger, less resistant Purisima Formation about a mile east of Natural Bridges where cliff erosion begins to proceeds more rapidly. Much of this section of coast has been armored in the last 30 to 40 years, predominantly with riprap (Griggs et al., 2005). In this 10-mile stretch of coast, 5 miles of shoreline, or 50%, are protected by armor.

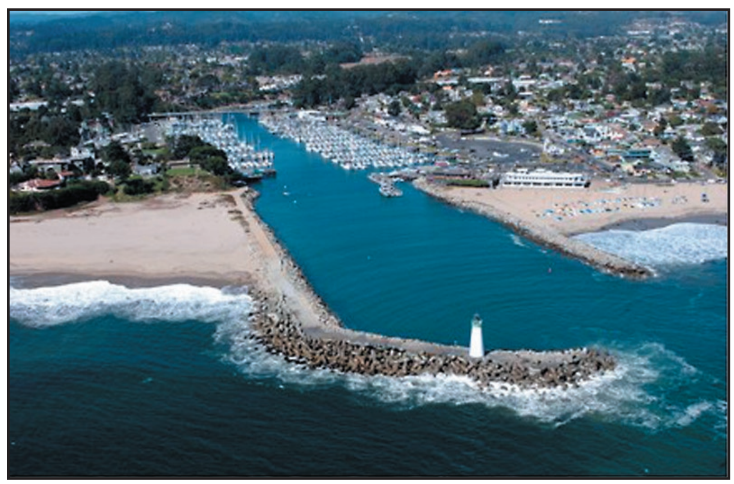

Fig 3.6: Santa Cruz Small Craft Harbor, California. Copyright © 2004 Kenneth & Gabrielle Adelman

Construction of the Santa Cruz Small Craft Harbor (Figure 3.6), located in the southern reach of the littoral cell, was initiated in 1963 by dredging a coastal lagoon and stabilizing an entrance channel with two parallel rubblemound jetties (completed in 1965) (Griggs et al., 2005; Wiegel, 1994). The west jetty is 1,200-feet-long with the ocean-end formed into a 300-foot-long dogleg angling toward the entrance. The east jetty is 810 feet long. The harbor was initially dredged to a depth of 20 feet and is 125 feet wide at the end of the jetties. Since 1986, routine dredging has been done with the harbor's own dredge (the Seabright), which operates nearly continuously during the winter and spring seasons at a cost of ~$500,000 annually (Wiegel, 1994). Following construction of the harbor, Seabright Beach, located west of the entrance and adjacent to the upcoast jetty, accreted rapidly, while beaches downdrift, or east of the entrance, experienced significant erosion. Capitola Beach, located approximately 3.5 miles downdrift of the harbor, disappeared within several years after completion of the harbor. A 250-foot-long groin was constructed at the downcoast end of Capitola beach in an attempt to stabilize the beach (Griggs, 1990). Beginning in 1965, dredging of the harbor entrance has provided sand to feed the downcoast or eastern beaches, including Capitola Beach, resulting in essentially equilibrium conditions in the area since the 1970's (Wiegel, 1994). Approximately five miles east of the harbor, at New Brighton State Beach, beach profiles indicate no long-term changes in the shoreline position since the 1970's (Wiegel, 1994).

Immediately up- and downcoast of Capitola, the irregular shoreline is backed by 50- to 75-feet high bluffs. Most of this area is devoid of beaches, with the exception of beaches in Capitola at the mouth of Soquel Creek, which has been widened due to a groin.

New Brighton State Beach to Monterey Submarine Canyon: South of New Brighton State Beach, in the southern portion of Santa Cruz County, the remaining shoreline of the Santa Cruz littoral cell is within the protected inner portion of Monterey Bay. Wide, sandy beaches provide a buffer for the bluffs from wave attack. From New Brighton Beach to La Selva Beach, seacliffs forming the seaward edge of a marine terrace reach to ~100 feet in elevation. From Manresa Beach to the Pajaro River, the terrace disappears and the coastline is dominated by Pleistocene-aged and recent sand dunes. During severe storms, these dunes undergo significant erosion. This erosion is subsequently followed by a period of dune accretion and growth (Griggs et al., 2005). South of the Pajaro River, wide sand dunes, reaching as high as 100 feet, back the beaches.

LONGSHORE TRANSPORT AND LITTORAL CUT-OFF DIAMETER

The dominant waves from the northwest drive net littoral drift to the south along the entire cell (Best and Griggs, 1991a; Habel and Armstrong, 1978). Potential littoral drift rates have been calculated in the vicinity of Santa Cruz Small Craft Harbor (Anderson, 1971; Walker and Dunham, 1978). Moore (1972) and Walker and Dunham (1978) estimated the littoral drift in the vicinity of the Santa Cruz Small Craft Harbor to be ~250,000 and ~300,000 yd^3/yr respectively, based on the accretion rates against the upcoast jetty of the harbor. Walker and Williams (1980) suggest that ~175,000 to 375,000 yd^3/yr bypass the harbor mouth. Seymour et al. (1980), however, concluded that bypassing of the harbor mouth is minimal.

Best and Griggs (1991a; 1991b) determined that the littoral cut-off-diameter, or the smallest grain size that will remain on the beach, for the Santa Cruz littoral cell is 0.18 mm. Sand finer than 0.18 mm will be transported and ultimately lost offshore, and thus is not a component of the sand budget. Fluvial transport in this cell is low relative to other littoral cells in California due to the small number of coastal streams delivering only minimal amounts of littoral-sized sand to the shoreline. In addition, resistant bluffs and cliffs consisting of Santa Cruz Mudstone and the Purisma Formation do not provide a great deal of sand that is sufficiently coarse to remain on the beaches (Best and Griggs, 1991b; Best and Griggs, 1991a). Headlands also hinder littoral transport by trapping sand in pocket beaches and preventing the continuous downdrift movement of the sand.

Harbor dredging can be used as an indicator of littoral drift assuming that the mouth of the harbor is an effective and efficient trap for littoral sand. From 1965 to 2004, an average of ~160,000 yd^3/yr of sand has been dredged from the entrance to the Santa Cruz Small Craft Harbor (Table 3.1).

Year	Yd^3/Yr	Year	Yd^3/Yr
1965	70,000	1985	145,200
1966	34,000	1986	207,000
1967	57,000	1987	206,400
1968	60,000	1988	230,400
1969	79,000	1989	214,500
1970	94,700	1990	173,600
1971	108,300	1991	163,300
1972	90,000	1992	220,600
1973	109,000	1993	124,300
1974	60,000	1994	234,400
1975	91,000	1995	170,700
1976	98,000	1996	101,900
1977	199,000	1997	118,200
1978	55,000	1998	399,300
1979	162,000	1999	317,900
1980	190,300	2000	262,300
1981	187,000	2001	242,000
1982	138,200	2002	348,000
1983	154,500	2003	220,000
1984	79,500	2004	180,000

Table 3.1: Annual dredging volumes in the entrance channel of the Santa Cruz Small Craft Harbor

Following harbor construction the beach west of the entrance, Seabright Beach, accreted quickly, eventually approaching a near equilibrium width around 1977 (Wiegel, 1994). With an equilibrium upcoast beach, littoral drift moves sand around the west jetty where it is trapped in the harbor mouth until it is dredged and placed on the downdrift beach. From 1977-2004, after Seabright Beach reached a point of near equilibrium, the Santa Cruz Small Craft Harbor has dredged an average of ~194,500 yd^3/yr of sand from the entrance channel and placed it on the beaches downdrift (easterly) (Table 3.1). Seabright Beach did continue to widen slightly for about the next decade, but over the past 20 years appears to have stabilized; the annual dredging volume over this last 20-year period, therefore is higher and has averaged ~214,000 yd^3. With 40 yrs of history, dredging from the entrance channel of Santa Cruz Small Craft Harbor provides the most reliable indicator of littoral drift in the southern portion of the Santa Cruz littoral cell which is estimated to range from ~180,000 to ~220,000 yd^3/yr.

SAND SOURCES

River Input: The main fluvial source of sand to this littoral cell is the San Lorenzo River (Figure 3.7), which discharges ~1 mile west of the Santa Cruz Small Craft Harbor. Small coastal streams draining the Santa Cruz Mountains in San Mateo and Santa Cruz counties provide additional sand to the Santa Cruz littoral cell. Thirteen streams with basins greater than 5 square miles drain 85% of the 274 square mile region from Tunitas Creek to Santa Cruz Harbor (Best and Griggs, 1991a). The mouths of the majority of these streams have been drowned by Holocene sea level rise resulting in low gradient flood plains and coastal lagoons, which serve as temporary sand storage sites. During the dry summer months, sand bars are commonly observed at the mouths of the streams (Figure 3.2). In addition, the construction of Highway 1 and railroad fill has prevented many coastal streams from reaching the ocean directly, leading to significant sediment impoundment during the past century.

Fig 3.7: Mouth of the San Lorenzo River. Copyright © 2002 Kenneth & Gabrielle Adelman

From Tunitas Creek south to Santa Cruz Harbor, Best and Griggs (1991a) used existing stream discharge and sediment transport data, collected additional data and used drainage basin comparisons to calculate that rivers, creeks, and streams provide an upper limit average of approximately ~114,000 yd^3/yr of littoral-sized sand (0.18 mm). South of Santa Cruz Harbor, the Pajaro River (Figure 3.8) currently contributes an average of ~60,500 yd3/yr of sand-sized material (coarser than 0.0625 mm) (Willis and Griggs, 2003; Willis et al., 2002). This is an upper limit to the sand supplied to the beaches from the Pajaro River because sand between 0.0625 mm and 0.18 mm will be lost permanently offshore. Damming of the Pajaro River has reduced the sand discharge by 6% from 64,000 yd^3/yr under natural conditions (Willis and Griggs, 2003; Willis et al., 2002). Overall, streams currently contribute ~174,500 yd^3/yr to the sand budget in the Santa Cruz littoral cell representing 81% of the present-day littoral budget (Table 3.2).

Fig 3.8: The Pajaro River mouth. Copyright © 2002 Kenneth & Gabrielle Adelman

Gully Erosion: Gully erosion results from soil piping through more permeable subsurface horizons that typically collapse as they enlarge producing gullies and channelized overland flow (Swanson, 1983). Extensive gully erosion is prevalent along the coastal hills in the northern San Mateo County portion of the littoral cell. Gullying tends to be confined to the alluvial and colluvial marine terrace deposits overlying the Purisma Formation. Using ground coverage, depth and width of gullies as well as material being eroded, it was determined that gully erosion adds an estimated 38,000 yd^3/yr of sediment to the shoreline; however, 80-90% of this material is too fine to remain on the beaches (Best and Griggs, 1991b; Best and Griggs, 1991a). Using the littoral-cut-off diameter (0.18 mm), gully erosion in the northern portion of this cell provides a maximum of ~7,600 yd^3/yr of sand to the budget (Best and Griggs, 1991b; Best and Griggs, 1991a). Overall, gully erosion represents 4% of the present-day sand supplied to the cell (Table 3.2).

Cliff Erosion: Quaternary aged marine terraces fronted by actively eroding, near vertical seacliffs ranging in height from 10- to 165-feet line ~63 miles of the 75-mile-long shoreline of the Santa Cruz littoral cell. These cliffs or bluffs are often capped with terrace deposits ranging from 5 to 40 feet in thickness (Best and Griggs, 1991b; Best and Griggs, 1991a; Hapke and Richmond, 2002). Santa Cruz Mudstone, the Pigeon Point Formation (consisting of well indurated silts, sands and gravel), and the Purisima Formation (consisting of mudstone, siltstone and very fine-grained sandstone) are exposed in the seacliffs in this littoral cell. Quaternary dunes, terrace deposits and alluvium cap the bluffs at Año Nuevo. Pocket beaches exist where coastal streams and creeks interrupt the cliffed coastline.

Reduction to the Sand Supply in the Santa Cruz Littoral Cell			
Inputs	**Natural (cy/yr)**	**Actual (cy/yr)**	**Reduction (cy/yr)**
Rivers	196,000	190,000	5,000 (3%)
Bluff Erosion	41,000	33,000	8,000 (20%)
Santa Cruz Littoral Cell Sand Budget Components			
Sand Source	**Historic: Including Año Nuevo Sand Reserve**	**Present Day: Excluding Año Nuevo Sand Reserve**	
Rivers	174,000 (66%)	174,000 (81%)	
Bluff Erosion	33,000 (12%)	33,000 (15%)	
Gully/Terrace Erosion	8,000 (3%)	8,000 (4%)	
Sand from Año Nuevo Reserve	50,000 (19%)	0 (0%)	
Total Littoral Input	265,000 (100%)	215,000 (100%)	

Table 3.2: Overall sand contributions and reductions to the Santa Cruz littoral cell. Reductions to river sand yields are reported in this table only for the San Lorenzo and Pajaro rivers and San Gregorio, Pescadero and Soquel creeks. In addition, these estimates are for sand coarser than 0.0625 mm or the sand/silt break point. The littoral cut-off diameter for this cell is 0.18 mm; thus the sand contribution to the sand budget in this cell from rivers is somewhat less than reported under the "actual" conditions in this table. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and generated from seacliffs through erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and shoreline armoring. Sand contributions to the budget for the Santa Cruz littoral cell, and the subsequent percentages, are shown including the sand from the reserve at Año Nuevo (which is currently depleted) and when excluding it.

Seacliff erosion rates vary in this littoral cell from nearly undetectable along the resistant headlands and cliffs of the Pigeon Point Formation, to moderate in the Purisima Formation (0-8 in/yr), to high (up to ten feet per year) near Año Nuevo Point. The Santa Cruz Mudstone and the Purisima formation are fine-grained and contribute a negligible amount of littoral-sized sand (coarser than 0.18 mm) to the sand budget in this cell. Erosion of the coastal cliffs and bluffs from Tunitas Creek to Santa Cruz Harbor only contribute between 16,000 and 26,000 yd^3/yr (an average of 21,000 yd^3/yr will be used in this analysis) (Best and Griggs, 1991b; Best and Griggs, 1991a). South of Santa Cruz Harbor, erosion of the bluffs, which are also comprised of the Purisima Formation, contributes ~10,000 yd^3/yr of sand sized material. An additional ~10,000 yd^3/yr of littoral-sized sand is produced by the cliffs between Half Moon Bay and Tunitas Creek (Limber, 2005). In total, under natural conditions, seacliff erosion contributes an average of ~41,000 yd^3/yr of sand to the Santa Cruz littoral Cell (Table 3.2).

Fig 3.9: Coastal armoring along West Cliff Drive, Santa Cruz
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Shoreline armoring protects 8 miles of seacliffs in the Santa Cruz Littoral Cell. The majority of the shoreline armoring is located in the developed portion of Santa Cruz County (Figure 3.9). Coastal armoring prevents an estimated 8,000 yd^3/yr (20% reduction) of sand from entering the littoral cell through seacliff erosion. Thus, by taking shoreline armoring into account, seacliff erosion adds ~33,000 yd^3/yr of sand to the Santa Cruz littoral cell, representing 15% of the sand in the present-day overall littoral budget (Table 3.2).

Dunes: Modern sand dunes are found at the mouths of Pescadero, San Gregorio, Waddell and Scott creeks. In addition, sand dunes overlie marine terrace deposits at Año Nuevo, Franklin Point, and Sand Hill Bluff. Best and Griggs (1991a) determined that there is minimal sand transferred today from the beaches in this cell to the dunes and vice versa at Franklin Point and Sand Hill Bluff due to the relatively small size of these dune fields. Thus, these dunes do not significantly impact the sand budget for the Santa Cruz littoral cell.

Once Año Nuevo Island was isolated from the mainland, sand that was previously retained behind the point, which was serving as a natural groin, was now free to flow south as littoral drift. An average of ~50,000 yd^3/yr of sand was added to the budget of the Santa Cruz littoral cell from the reserves at Año Nuevo (Griggs et al., 2005; Seals, 2005). However, the 13 to 20 million cubic yards of sand that was estimated to have been retained by the point has now been exhausted. Beaches downdrift or south of Año Nuevo may start to narrow with a reduction in this sand source (Griggs et al., 2005; Seals, 2005). Historically, Año Nuevo sands accounted for 19% of the overall sand in the budget for the Santa Cruz littoral cell, reducing the importance of sand provided by river, seacliffs, and gullying (Table 3.2). Without the sand supplied by Año Nuevo, rivers now represent 81% of the sand budget with seacliffs and gully erosion providing the remaining 15% and 4% of sand respectively. More research needs to be done in this vicinity to determine the potential impact to the downcoast beaches resulting from the loss of this estimated 50,000 yds^3 of sand annually from this former sand source.

Beach Nourishment: Harbor bypassing is the only regular form of beach nourishment practiced in the Santa Cruz littoral cell (Wiegel, 1994). As previously stated, bypassing at Santa Cruz Harbor has provided an average of ~160,000 to ~220,000 yd^3/yr of sand to beaches downdrift or east of the harbor. In 1969, following the loss of Capitola beach as a result of sand trapping by the jetties at the Santa Cruz Small Craft Harbor, 27,000 yds^3 were trucked in to rebuild the beach. There has been no other form of beach nourishment in this littoral cell.

SAND SINKS

Submarine Canyon: Monterey Submarine Canyon is the main sand sink effectively terminating the Santa Cruz littoral cell. The head of the canyon is located at Moss Landing (Figure 3.10), ~20 miles southeast of the Santa Cruz Small Craft Harbor. Three branches of the submarine canyon extend to within 300 feet of shore capturing littoral drift and terminating the littoral cell (Best and Griggs, 1991b; Best and Griggs, 1991a). It is estimated, through budget analysis, that ~265,000 yd^3/yr of sand, on average, is lost into the Monterey Submarine Canyon from the Santa Cruz littoral cell.

Fig 3.10: Moss Landing Harbor. The head of Monterey Submarine Canyon reaches nearly to the harbor entrance. Copyright © 2002 Kenneth & Gabrielle Adelman

Offshore Transport: Movement of sand on- and offshore across the shelf is a potentially significant factor in the development of a sand budget for a littoral cell. Storage on the inner shelf is a difficult component to quantify (Bowen and Inman, 1966). With such large shelf areas typically involved, a small increase in the thickness of the sand veneer can produce a large volume of sand storage. However, there have been no studies addressing this transfer or storage of littoral-sized sand (0.18 mm for the Santa Cruz littoral cell) for the offshore region of the Santa Cruz littoral cell. Due to the research required to evaluate this component, on- and offshore estimates were not attempted in this study. It is assumed that on- and offshore transport is in equilibrium resulting in a zero net gain or loss for this littoral cell. At depths greater than 80 ft, offshore sampling across the shelf revealed that nearly all of the sediment is finer than the littoral-cutoff diameter (0.18 mm) suggesting that the there is not a significant transfer of material offshore (Best and Griggs, 1991a; Lee et al., 1970; Yancey et al., 1970). Recent multibeam bathymetry done by the USGS north of Santa Cruz confirms that there is significant movement of sand at depths of 10-20 meters along the inner shelf although not enough work has been done over time to indicate whether or not there is net transport, on or offshore (Curt Storlazzi, personal communication).

SUMMARY OF THE SAND BUDGET FOR THE SANTA CRUZ LITTORAL CELL

The sand budget for the Santa Cruz littoral cell is summarized in Figure 3.11 as a simple box-model and in Figure 3.12 as a running, alongshore, mile-by-mile budget. From Pillar Point to the Santa Cruz Small Craft Harbor, sand is presently supplied to the beaches by streams (~114,000 yd^3/yr), gully and terrace degradation (~8,000 yd^3/yr), cliff erosion (~23,000 yd^3/yr), and formerly supplied by the distribution of sand retained in the sand at Point Año Nuevo (~50,000 yd^3/yr). Sand supply in the northern reach of the cell totals ~195,000 yd^3/yr.

The surplus of sand that existed on the Año Nuevo peninsula has now been depleted, and the beaches at Año Nuevo point have thinned drastically over the past 150 years (Griggs, Patsch and Savoy, 2005). Rough estimates indicate that as much as 12 to 18 million yds^3 of additional sand-sized sediment was made available to littoral drift over the past 200 to 350 years. During that time the normal flow of littoral sand was apparently augmented by many tens of thousands of cubic yards of additional sand on an annual basis. This suggests that the downcoast beaches including the beaches of northern Monterey Bay widened as a result. The most interesting conclusion that can be inferred from the changes at Año Nuevo Point is that once the tail end of this point source of sand moved southward along the coast, the once-wide beaches may begin to slowly thin. This may lead to increased cliff and bluff retreat (Griggs, Patsch and Savoy, 2005). To date, however, there has been no reduction in the annual volumes of sand dredged from the Santa Cruz Harbor (Table 3.1). With all of the other fluctuations and perturbations in the source inputs and littoral transport rates, changes in sand supply on the order of 50,000 yd^3/yr may simply not be observable or recognizable.

The Santa Cruz Small Craft Harbor dredges ~200,000 yd^3/yr of sand from its entrance channel which is placed on the downdrift, or eastern, beaches. This sand, in addition to the sand supplied through seacliff erosion (~10,000 yd^3/yr) and from the Pajaro River (~60,500 yd^3/yr) feeds the beaches in the southern reach of the cell. Littoral drift travels around the northern margin of Monterey Bay until it eventually reaches the head of the Monterey Submarine Canyon where it is funneled offshore and lost permanently to the littoral cell sand budget. It is estimated that ~265,000 yd^3/yr of sand is lost into Monterey Submarine Canyon from the Santa Cruz littoral cell.

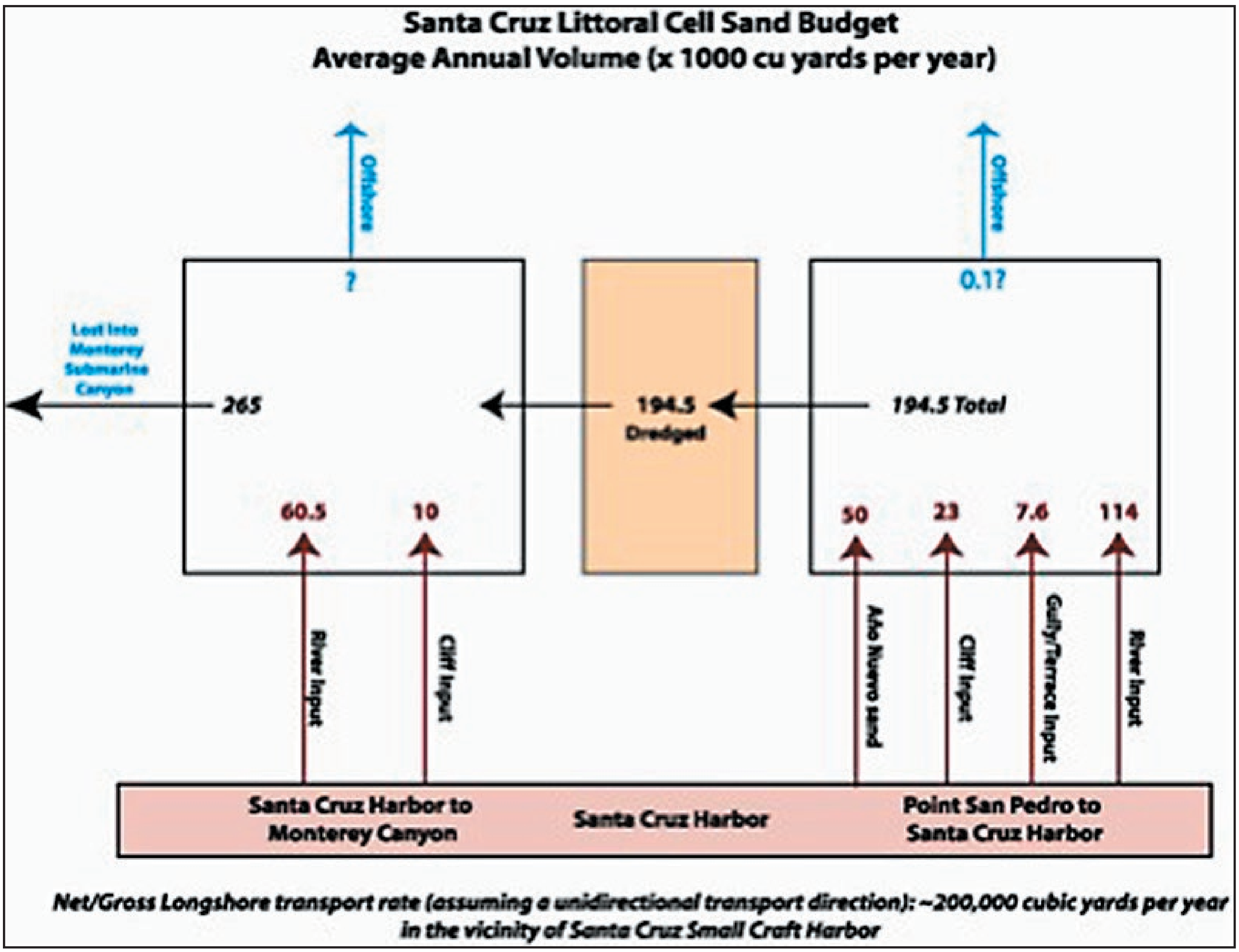

Fig 3.11: Box-model sand budget for the Santa Cruz littoral cell. The 50,000 yd3/yr of sand supplied by Año Nuevo is no longer being added to the littoral budget. Thus, the sand budget is not currently balanced, which may result in the narrowing of beaches downdrift of Año Nuevo.

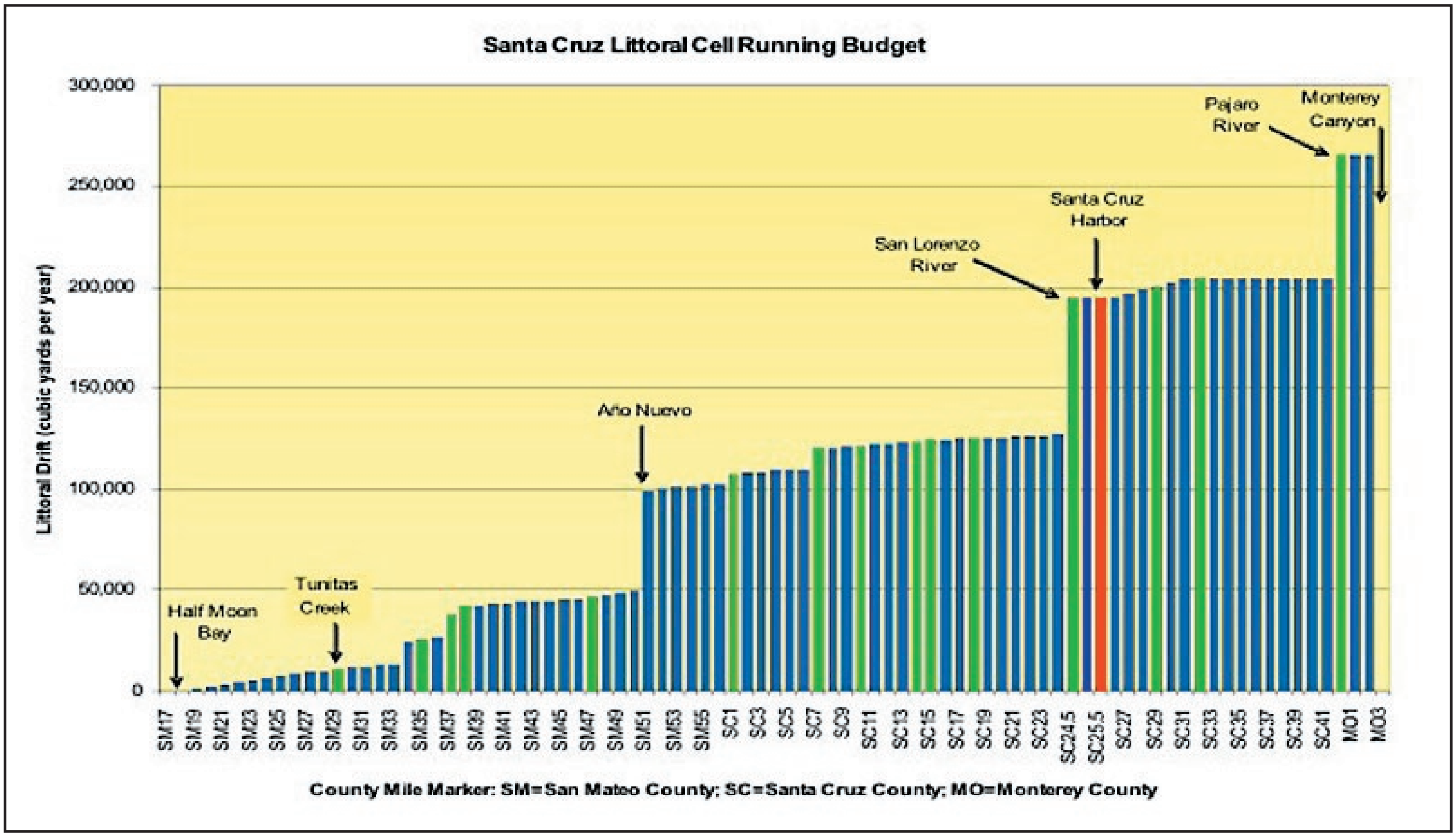

Fig 3.12: Running mile-by-mile sand budget for the Santa Cruz littoral cell. Stream inputs are shown in green. Santa Cruz Small Craft Harbor is shown in red and serves as a check point for the cell budget. Other inputs include cliff erosion both north and south of the harbor, gully degradation north of the harbor, and sand from Año Nuevo's sand reserve, which is now depleted resulting in a negative balance of the budget. If the budget is slightly negative, the beaches in the southeastern portion of the cell may narrow.

CHAPTER 4

SOUTHERN MONTEREY BAY LITTORAL CELL

The 20-mile stretch of coastline, from Moss Landing to the Monterey Peninsula, comprising the Southern Monterey Bay littoral cell (Figure 4.1), consists of wide, sandy beaches backed by broad coastal lowlands and extensive late-Pleistocene sand dunes rising to heights of 150 feet. Over the past several thousand years, the Salinas and Pajaro rivers delivered large volumes of sand to the shoreline along this stretch of coast. The large quantity of sand in combination with a dominant, on-shore wind and a broad, low-lying back beach allowed for the creation of the broad beaches and large dunes seen today (Figure 4.2) from Sunset Beach to Monterey (Griggs et al., 2005).

Southern Monterey Bay's beaches and dunes are in an erosive state meaning that more sand is removed than is being supplied. This is in part due to sea level rise but also to the large beach sand mining operations that were common in this area from the early 1900's until approximately 1990. Dune erosion, which occurs with the recession of the bluff-top edge of the dune, nourishes the beaches throughout the cell. In addition to the sand supplied to the beaches through dune erosion, sand is added to this littoral cell from the Salinas River located near the north end of the cell.

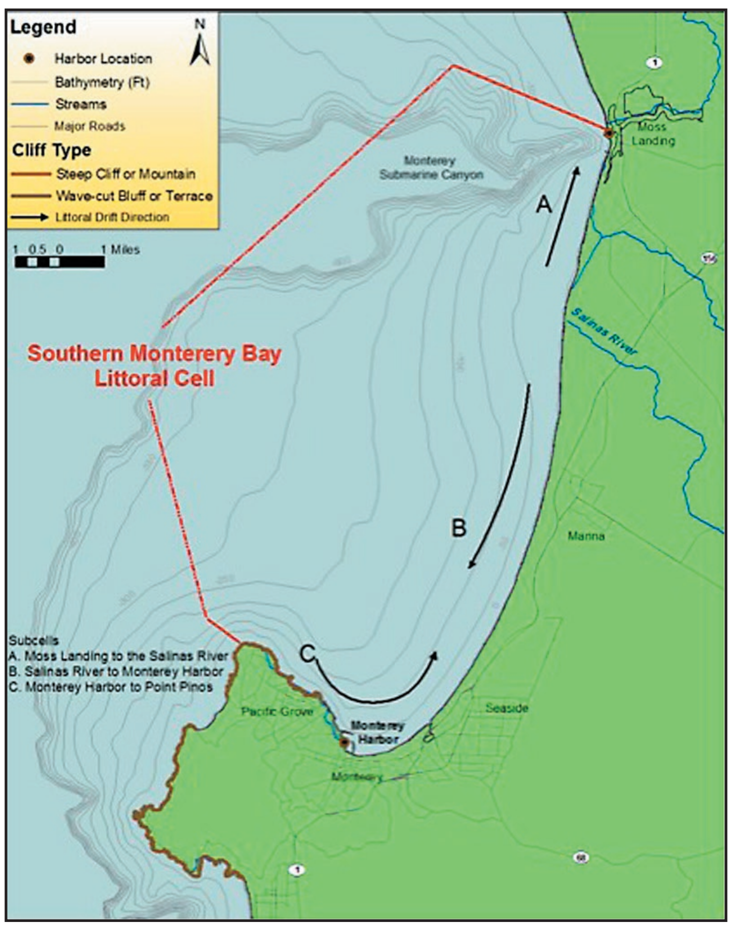

Fig 4.1: Southern Monterey Bay Littoral Cell Location Map

Fig 4.2: South end of the City of Marina. Copyright © 2004 Kenneth & Gabrielle Adelman.

LONGSHORE TRANSPORT

Three sub-cells have been identified within the larger Southern Monterey Bay littoral cell essentially delineated by differing littoral transport directions (Habel and Armstrong, 1978). Due to the refraction of waves as they travel over Monterey Submarine Canyon and the delta offshore of the Salinas River, littoral drift between the Salinas River and Moss Landing is dominantly to the north, creating the northern sub-cell (Figure 4.1) (Habel and Armstrong, 1978; Thornton et al., 2006). South of the Salinas River to Monterey Harbor (Figure 4.1) littoral drift is directed to the north and south (Habel and Armstrong, 1978; Thornton et al., 2006). Where the north and south longshore currents converge, rip currents develop and carry sand offshore. South of Monterey Harbor, waves are refracted around the large granitic promontory of Monterey Peninsula forming the southern sub-cell between Point Piños, the northernmost tip of the peninsula and Monterey Harbor (Figure 4.1) (Habel and Armstrong, 1978).

Since its construction, Monterey Harbor (Figures 4.1 and 4.3) has required no maintenance dredging in its entrance channel. This is a good indication that this is the boundary of a sub-cell within the greater Southern Monterey Bay littoral cell such that no sand is traveling into the cell as littoral drift from the Monterey Peninsula. Evidence for the delineation of the third sub-cell, from Point Piños to the Monterey Harbor includes drastic differences in lithology, coastal orientation and beach mineralogy.

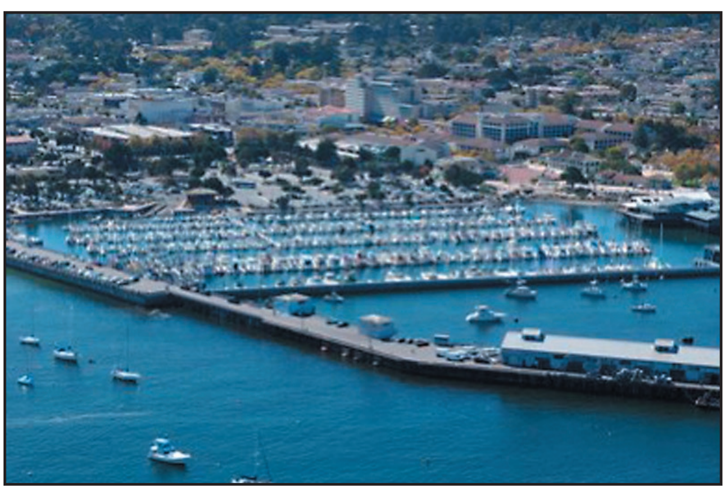

Fig 4.3: Monterey Municipal Wharf and Marina, Monterey Copyright © 2004 Kenneth & Gabrielle Adelman.

Beaches on the peninsula in the third sub-cell are formed of coarse-grained, angular, granitic materials, while sand on the beaches in the second sub-cell, from Monterey Harbor to the Salinas River are composed of fine-grained, rounded, quartz material derived from the erosion of the southern Monterey Bay dunes (Storlazzi and Field, 2005; Thornton et al., 2006).

Fig 4.4: Mouth of the Salinas River, 2004 Copyright © 2004 Kenneth & Gabrielle Adelman.

RIVER INPUT

Until 1910, the Salinas River, after flowing northwards parallel to the shoreline, discharged into Elkhorn Slough, a large estuary in the center of Monterey Bay, just landward of the head of Monterey Canyon. In 1910, the river broke through the narrow stretch of dunes separating the river from the ocean at approximately its current location (Figure 4.4). At that time, a dike was constructed to hold the channel in its present location and prevent the river from entering its former channel (Griggs et al., 2005). The bathymetric contours of the pre-historic submarine Salinas River delta radiate outward from the present mouth of the river (Figure 4.1), however, suggesting that the present mouth may have been the discharge point for an extended period of time in the Pleistocene.

In its undisturbed (pre-dammed) condition the Salinas River yielded ~726,000 yd^3/yr of sand (coarser than 0.0625mm); however, damming of the river has reduced the sand discharge by 33% to ~489,000 yd^3/yr (Willis and Griggs, 2003). These sand transport volumes are based on data from the closest gauging station to the mouth (at Spreckels), located 12 miles upstream from the coast. It is believed that much of the sand may be deposited along the low gradient lower reach of the river with additional sand lost to the floodplain during over-bank flooding, such that these volumes may be too high. Yet these are the best actual data available and will be used in the budget. Currently, the Salinas River contributes 58% of the sand to the overall sand budget in the Southern Monterey Bay littoral cell (Table 4.1). Most of this sand is driven northward by the dominant littoral drift and is eventually carried into one of the active nearshore tributaries of Monterey Submarine Canyon. During major floods in the recent past, however, some Salinas River sand has been traced southward along the shoreline, using heavy mineralogy (Combellick and Osborne, 1977).

Southern Monterey Bay			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	726,000 (57%)	489,000 (58%)	237,000 (33%)
Dune Erosion (1940-1984)	353,000 (33%)	353,000 (42%)	0 (0%)
Sand Mining (1940-1984)	Na (Na)	Na (Na)	180,000 (Na)
Total Littoral Input	1,079,000 (100%)	842,000 (78%)	417,000 (39%)

Table 4.1: Over-all sand contributions and reductions to the Southern Monterey Bay littoral cell. Reductions in the sand supply are due to the damming of the Salinas River and sand mining operations prevalent in this area from 1940 through the 1990's. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through dune erosion or recession. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply.

SAND DUNES

Large sand dunes, reaching heights of up to 150 feet along the shoreline of the Southern Monterey Bay littoral cell, are geologically young (approximately 3,000 to 5,000 years old), but are now cut-off, for the most part, from their beach sand sources due to coastal erosion associated with sea level rise (Figure 4.2). These dunes were created during the Pleistocene from sand deposited along the exposed continental shelf by the Salinas and Pajaro rivers. Prevailing winds blew this surplus of sand onshore to create the massive sand dunes seen today (Thornton, et al, 2006).

Dune erosion is highly episodic, and occurs when large storm-generated waves coincide with high tides (Dingler and Reiss, 2002). This erosion is exacerbated during El Niño winters when storm waves intensify. Erosion of the dunes occurs more often in the winter months when storms are more powerful and frequent, and when the protective fronting beaches are narrower, thus leaving the dunes exposed and vulnerable to erosion. Dune erosion occurs when wave swash or run-up undercuts the base of the dunes causing the overlying sand to slump onto the beach (McGee, 1987). This sand is washed out with the retreating waves where most of it becomes part of the littoral drift system.

Thornton et al (2006) determined long-term erosion rates for the dunes in this cell to be on the order of 1.6 ft/yr in the south end of the central sub-cell near Monterey, increasing to a maximum of 5 feet/yr around Seaside and subsequently decreasing northwards towards the Salinas River. Overall, from 1940-1984, dune erosion or recession has contributed ~353,000 yd^3/yr of sand to the littoral cell, representing 42% of the overall sand budget (Thornton, et al, 2006; Table 4.1). This volume includes the El Niño winters of 1957-1958 and 1982-1983.

The large El Niño winter of 1997-1998 resulted in extensive erosion of the beaches and dunes at Fort Ord, Marina, Sand City and Monterey. Thornton et al. (2006) estimate that a total of ~3,392,000 yds^3 of sand was eroded from the dunes and beach during this El Niño winter. Specifically, ~2,380,000 yds^3 of sand eroded from the dunes (over 6 times the long-term annual average), and ~1,011,000 yds^3 of sand eroded from the beaches in this cell. The majority of the eroded beach sand will be stored in offshore bars that form during the winter and return to the beaches with the summer swell. Some sand, however, is lost permanently from the system during these large storm events due to transport across the inner shelf.

SUBMARINE CANYONS

Monterey Submarine Canyon, one of the world's deepest and largest submarine canyons, is the main sink of sand for the Southern Monterey Bay littoral cell. Three branches of the submarine canyon extend to within 300 feet of shore, capturing littoral drift and terminating the littoral cell. Sand traveling south from the Santa Cruz cell to the north, and from the southern portion of Monterey Bay is carried down the canyon by turbidity currents and deposited miles offshore, effectively removing the sand from the littoral cells.

SAND MINING

The largest anthropogenic sink for sand in the Southern Monterey Bay littoral cell has historically been sand mining. Beach sand mining began in 1906 at the mouth of the Salinas River. By the 1950's, mining operation had expanded to six commercial sites at Marina and Sand City (Habel and Armstrong, 1978; Magoon, 1972). Beach-sand mining operated unregulated until 1968 when leases were issued and managed by the State Lands Commission. In 1974, the U.S. Army Corps of Engineers put additional regulations in place. Leases on all but one beach mining operations expired in the late 1980's. As of 1990, mining of the surf zone was discontinued.

However, one mining operation still exists on the beach at Marina (Figure 4.5) where sand is dredged from the back beach, and therefore, effectively removed from the littoral system. Sand mining from the back dunes was also common in this area and is still underway in Marina, however, dune sand mining does not directly impact the littoral sand budget, and thus, is not included in this report.

Fig 4.5: Back beach sand mining operation in Marina. Copyright © 2004 Kenneth & Gabrielle Adelman.

Between 1940 and 1984, Thornton et al (2006) estimate that on average ~167,000 yd^3/yr of sand were mined from the beaches of the cell, resulting in the permanent loss of this sand (Table 4.1). Data released recently by the Army Corps of Engineers on the sand mining history of southern Monterey Bay indicates a slightly higher figure of 180,000 yd^3/yr removed during the 50-year period from 1940-1990.

SUMMARY OF THE SAND BUDGET

The Southern Monterey Bay littoral cell is a complicated network of sand sources, littoral transport, and sinks. Due to the lack of a uniform littoral transport direction in this cell, an alongshore, running, mile-by-mile sand budget was not appropriate. Three sub-cells exist within the larger framework of the Southern Monterey Bay cell: Monterey Submarine Canyon to the Salinas River, the Salinas River to Monterey Harbor, and Monterey Harbor to Point Piños, the northernmost tip of the granitic Monterey Peninsula (Figure 4.1).

In the first sub-cell, from the head of Monterey Submarine Canyon to the Salinas River, littoral drift is dominantly to the north. Sand entering the cell from the Salinas River travels upcoast, nourishing the beaches until it is lost into the Monterey Submarine Canyon. Currently, the Salinas River is believed to discharge ~490,000 yd^3/yr of sand-sized material (0.0625 mm or coarser) (Willis and Griggs, 2003; Willis et al., 2002). Dams have reduced the original sand yield for the Salinas River by 33%, or ~237,000 yd^3/yr (Willis and Griggs, 2003; Willis et al., 2002).

From the Salinas River to Monterey Harbor littoral drift travels both north and south due to the orientation of the coastline and the nearshore bathymetry. Lateral or longshore transport within this sub-cell has been shown to be minimal (Philip Williams & Associates, 2004) with rip currents likely the dominant transport mechanism and sink such that sand moves predominantly offshore instead of alongshore (Thornton et al., 2006). The only significant source of sand in this sub-cell is from the erosion of dunes, which contributes ~353,000 yd^3/yr of sand (Thornton et al., in 2006). Sand mining, operating from the early 1900's until 1990, was the main anthropogenic reduction to the sand supply within this sub-cell. From 1940-1990, ~180,000 yd^3/yr of sand was permanently removed from the sub-cell. All but one beach sand mining operation have been terminated, thus reducing the importance of this historic sink. As previously stated, the main sink for sand in this sub-cell is believed to be the transport of sand offshore by rip currents. Monterey Harbor has not required significant maintenance dredging in its entrance channel since its construction indicating that sand is not moving alongshore as littoral drift into this area from the north. Sand does move from the Monterey Peninsula eastward towards the harbor as evidenced by the rapid development of the beach west of the harbor since the breakwater was emplaced (Storlazzi and Field, 2000).

From Monterey Harbor to Point Piños, the northern tip of the Monterey Peninsula, beaches are backed by low, resistant granitic cliffs. Beaches in this sub-cell consist of 1) material eroded from the porphyritic granodiorite out crops or deposited by streams and then carried eastward by waves and currents, and 2) relict sediments originally from the Salinas River to the north that have been transported onshore by northwesterly waves or wind during sea level low stands. Volumetric estimates of sand emanating from seacliff erosion were not made for this sub-cell.

CHAPTER 5

SANTA BARBARA LITTORAL CELL SAND BUDGET

The Santa Barbara littoral cell (Figure 5.1) is the longest littoral cell in southern California, extending 144 miles from the mouth of the Santa Maria River, around Point Conception, and terminating at Point Mugu into the Mugu Submarine Canyon (Patsch, 2004). At Point Conception, the California coastline makes an abrupt 90-degree shift from a north/south orientation to an east/west orientation. It has been concluded by many researchers (Azmon, 1960; Bowen and Inman, 1966; Judge, 1970; Trask, 1952) that Point Conception is only a partial barrier to littoral drift; sand moves around this promontory. From Point Conception to Santa Barbara Harbor, the shoreline generally consists of thin (less than 10 feet thick), narrow beaches backed by vertical cliffs or bluffs (Wiegel, 1994). Significant beach erosion has threatened development in the communities of Isla Vista and Goleta.

SANTA BARBARA LITTORAL CELL BOUNDARIES

Originally, Habel and Armstrong (1978) delineated the northern boundary of the Santa Barbara littoral cell at Point Arguello (south of the Santa Ynez River mouth); however, Patsch (2004) concluded that the boundary needed to be extended to include the Santa Maria River mouth. The large dune fields north of the Santa Maria River mouth suggest that most of the upcoast littoral sand is lost to inland sources at this location. In order to explain the average volume of sand dredged from Santa Barbara Harbor annually (~314,000 yd^3/yr), assuming a unidirectional southeastward littoral drift in this reach of coast, sand contributions from the Santa Maria and Santa Ynez rivers and San Antonio Creek must be included. The small, ephemeral, Santa Ynez mountain streams, east of Point Conception, which are the only significant sources of sand to this stretch of shoreline, do not provide enough sand annually (~195,000 yd^3/yr) to explain the volume of sand dredged from Santa Barbara Harbor. This sand deficiency as well as a number of historic studies that have argued for a more northerly boundary for the Santa Barbara cell that will be discussed below led us to use the mouth of the Santa Maria River as the upcoast boundary of the cell.

LITTORAL DRIFT

There are four harbors within this littoral cell (Santa Barbara, Ventura, Channel Islands and Port Hueneme harbors), which serve as constraints, or check points, for littoral drift rates when constructing a sand budget. Because these harbors essentially serve as nearly complete traps for littoral transport, the yearly dredging numbers from the harbors are believed to provide a reasonable proxy for annual littoral drift rates. Because

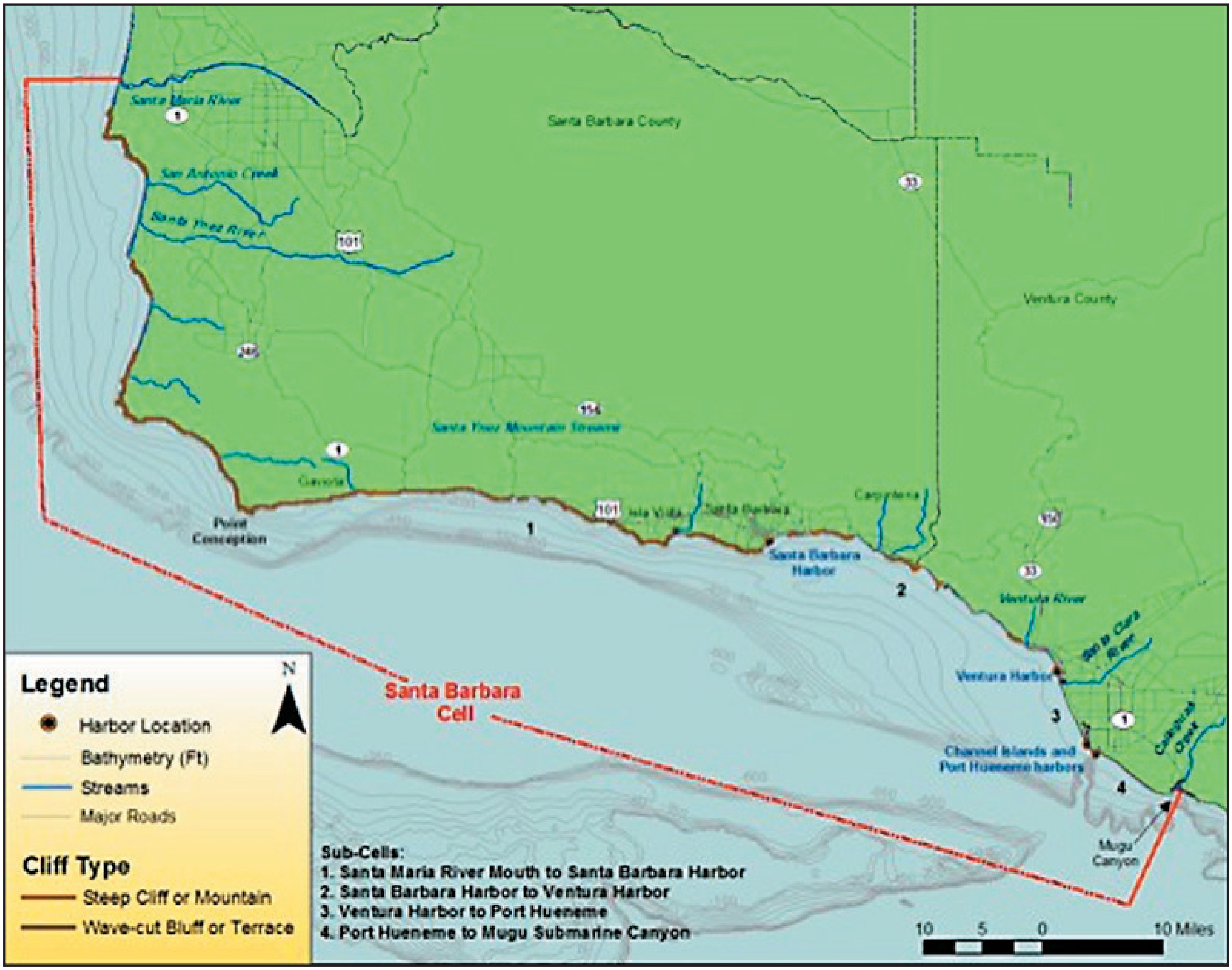

Fig 5.1: Location map for the Santa Barbara Littoral Cell

of the coastal orientation and essentially unidirectional trend of littoral drift in the southeastward direction, these drift rates are considered to represent both the net and gross transport rates. This cell is divided into four sections, with each harbor acting as a terminus: (1) Santa Maria River to Santa Barbara Harbor, (2) Santa Barbara Harbor to Ventura Harbor, (3) Ventura Harbor to Channel Islands Harbor/Hueneme Submarine Canyon, and (4) Hueneme Submarine Canyon to Mugu Submarine Canyon (Figure 5.1).

SAND SOURCES

Fluvial Inputs: The Santa Barbara littoral cell has four main rivers (Santa Maria, Santa Ynez, Ventura, and Santa Clara rivers) and a number of smaller streams (San Antonio Creek, Santa Ynez mountain streams, and Calleguas Creek (Figure 5.1), which together, currently contribute 99.5% (or an average of ~2,167,000 yd^3/yr) of sand to this littoral cell (Willis and Griggs, 2003; Willis et al., 2002). Before dam construction these rivers contributed ~3,643,000 yd^3/yr of sand to the cell (Table 5.1). Thus, dams have reduced the sand yield of these rivers by 40% or ~1,476,000 yd^3/yr (Willis and Griggs, 2003; Willis et al., 2002).

SEACLIFF/BLUFF EROSION

The seacliffs or bluffs in the Santa Barbara littoral cell are 10- to 100-feet high and are cut into uplifted marine terraces. The seacliffs expose a basal bedrock unit (either the Monterey Shale, which is a Miocene marine diatomaceous shale, or the Sisquoc Formation, a diatomaceous silty shale) and an overlying sequence of unlithified marine terrace deposits and soils, ranging in thickness from 5- to 50- feet. By sampling the Monterey and Sisquoc formations it was found that no beach-size material (0.125 mm or coarser in this cell) resulted from the breakdown and analysis of bedrock samples. Thus, the bedrock material exposed in the cliffs is not a significant contributor to the sand budget in this cell (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002). Terrace deposit samples were also analyzed and found to contain an average of 60% littoral or beach-size sand (coarser than 0.125 mm).

Erosion rates for the seacliffs in the Santa Barbara cell are not well documented. In Living with the Changing California Coast (Griggs, Patsch and Savoy, 2005), fifteen erosion rates throughout the length of the cell were reported. These rates range from 3-inches to 20-inches per year, overall a relatively narrow range. Based on these erosion rates and the littoral sand content of the cliffs, the overall "natural" sand contribution from seacliff erosion for the entire Santa Barbara Littoral Cell is estimated to be ~14,000 cubic yards per year (Table 5.1) (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002).

Seacliff failures have been devastating to many cliff-top developments in the Santa Barbara Cell. Seawalls, revetments or other armoring, including breakwaters, now protect 33 miles of the coastline in the Santa Barbara cell. Only 11 miles of this armoring is protecting seacliffs, however; the remaining armor is protecting back-beach development and harbors and is not impacting the natural sand supply to the coast from cliff erosion. The shore-parallel armor is estimated to be preventing approximately 3,000 cubic yards per year of sand from ending up on the beaches of the cell (Table 5.1). This represents almost 20% of the original or "natural" contribution to the littoral budget from seacliff erosion, although still a very small amount of sand (Patsch, 2004; Runyan, 2001; Runyan and Griggs, 2003; Runyan and Griggs, 2002).

Santa Barbara Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	3,643,000 (99.6%)	2,167,000 (99.5%)	1,476,000 (40.5%)
Bluff/Cliff Erosion	14,000 (0.4%)	11,000 (0.5%)	3,000 (19.4%)
Total Littoral Input	3,657,000 (100%)	2,178,000 (100%)	1,479,000 (40.4%)

Table 5.1: Overall sand contributions and reductions to the Santa Barbara littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Total natural input from seacliff erosion was ~14,000 cubic yards per year, which has been reduced to ~11,000 cubic yards annually due to construction of coastal armoring structures (Table 5.1). Thus, littoral sand inputs to the Santa Barbara cell at present total 2,178,000 cubic yards per year, of which stream input contributes 99.5% with seacliff erosion contributing the remaining 0.5% (Table 4.1). Prior to armoring, the cliffs contributed 0.4% of the entire sand supply to the cell. Cliff armoring has reduced the total sand input from seacliff erosion to the Santa Barbara cell by 3,000 cubic yards annually, or 0.1% of the total budget; however due to the increase in sand blocked by dams, the importance of seacliff erosion to the littoral budget is slightly increased.

BEACH NOURISHMENT

Harbor bypassing has been a significant form of beach nourishment in this sub-cell, and will be discussed in the subsequent sections. Bypassing does not introduce "new" sand to the system; thus, it is not considered a sand source with respect to the sand budget.

SAND SINKS

Submarine Canyons: Like most littoral cells in southern California, the major sinks for the Santa Barbara littoral cell are submarine canyons. Hueneme Submarine Canyon, located at the entrance to Port Hueneme, and Mugu Submarine Canyon both act as sand sinks. Before sand reaches Hueneme Canyon however, it is trapped in Channel Islands Harbor where it is dredged every other year (Table 5.2). The majority of this sand is placed downcoast of Port Hueneme, thus bypassing Hueneme Canyon. Dredged sand deposited downcoast of Hueneme Harbor travels as littoral drift until it eventually is intercepted and funneled into Mugu Submarine Canyon where it is permanently lost to the littoral cell. Mugu Canyon is a nearly complete littoral barrier and terminates the Santa Barbara littoral cell.

DUNES

Dune fields can be a source and sink of sand for a littoral cell sand budget. Where applicable, sand lost or gained from dunes will be discussed in the appropriate section, or sub-cell. Overall, losses to dunes remove ~100,000 yd^3/yr of sand from this littoral cell (Bowen and Inman, 1966).

SAND BUDGET FOR THE SANTA BARBARA LITTORAL CELL

Santa Maria River to Santa Barbara Harbor: Willis et al. (2002), using stream flow, sediment discharge and reservoir filling data, calculated the input of sand-sized material from the Santa Maria River, San Antonio Creek, Santa Ynez River, and also the streams draining the Santa Ynez Mountains between Point Conception and Santa Barbara. These streams provide approximately 260,000, 60,000, 345,000, and 195,000 yds^3/yr respectively, on average, for at a total of ~860,000 yds^3/yr from fluvial sources along this coastal segment (Willis and Griggs, 2003; Willis et al., 2002).

As discussed previously Runyan and Griggs (2003; 2002) determined that seacliff erosion from this stretch of coast presently contributes ~11,000 yds^3/yr of beach size material.

Bowen and Inman (1966) developed a sand budget along California's coast from just north of the Santa Maria River to Santa Barbara. Although the values for the river and seacliff erosion contributions have been updated, their estimates for sand lost to the dune systems between the Santa Maria River mouth and Point Arguello are still the best available data. Utilizing migration rates of sand dunes and their cross-sectional areas, Bowen and Inman (1966) estimated that ~100,000 yds^3/yr of sand are lost from this littoral cell due to wind transport onshore with storage in dune complexes.

A 1,425-foot long shore-parallel breakwater was completed in 1929 to establish Santa Barbara's small craft harbor (Figures 5.2 and 5.3). Originally, a 600-ft gap was left between the breakwater and the coastline to allow sand to move along the shore from the west, bypass the harbor, and maintain the beach on the downdrift side of the harbor. The plan, however, did not work as anticipated. Because of the wave shadow created behind the breakwater, sand began to fill in the harbor and became a navigational hazard. In order to remedy this situation, the breakwater was extended, on its westward side, to the shore in 1930.

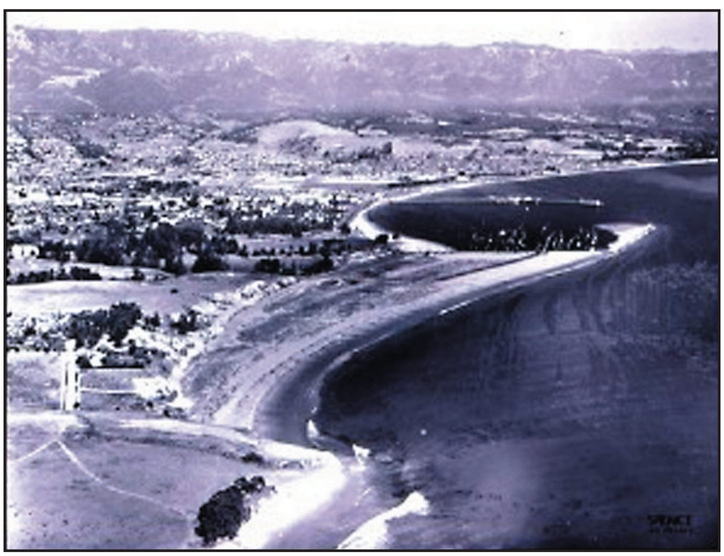

Fig 5.2: Santa Barbara Harbor: 1930's

The extension of the breakwater came with its own suite of problems, however. Sand began to accumulate on the upcoast side of the breakwater, pushing the shoreline seaward along the breakwater. The trapping of littoral drift on the western side of the breakwater essentially starved the beaches of sand on the downdrift side of the harbor. Sand also began to travel around the end of the breakwater and form a spit extending towards the shore (Figure 5.3); this soon became a navigational hazard. Consequently, in 1933, a sand-bypass system was developed that required sand to be dredged from the entrance channel of the harbor and used to nourish the downdrift beaches. Originally, the harbor was dredged every few years, however, in 1959, dredging became an annual procedure (Table 5.2). Santa Barbara Harbor's sand bypass/beach nourishment system has been operating for 72 years, and has set the precedent for all other sand bypass operations in California (Wiegel, 1965).

Fig 5.3: Santa Barbara breakwater and sand spit, 1989

Santa Barbara Harbor has dredged an average of ~314,000 cubic yards per year (1933-2004) of sand from its entrance channel and placed it on the downdrift beaches (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Noble Consultants, 1989; Wiegel, 1994). The configuration of the breakwater and associated sand spit (Figure 5.3), and the distance between the beach and the sand spit make littoral drift reversal and transport back to the dredging area very unlikely. It can be assumed then, that the average net longshore transport for this stretch of coast is ~314,000 cubic yards per year, equivalent to the average annual dredging volume.

Table 5.2 (Found on the following page): Dredging history for harbors in the Santa Barbara Littoral Cell (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Wiegel, 1994)

In order to balance the sand sources (+870,000 yd^3/yr) and sinks (-100,000 yd^3/yr) within this sub-cell (totaling ~770,000 yd^3/yr) with the known average annual rate of dredging in the Santa Barbara Harbor (~300,000 yd^3/yr), ~470,000 cubic yards of sand has to be lost from the system in one form or another from the reach of coast between the Santa Maria River mouth and the Santa Barbara Harbor (Figures 5.4 and 5.5). The 870,000 yd^3/yr includes ~665,000 yd^3/yr of sand from the rivers and streams north of Point Conception (reduced by losses to the dunes of 100,000 yd^3/yr) and an additional ~200,000 yd^3/yr from the streams draining the Santa Ynez Mountains southeast of Point Conception as well as inputs from cliff erosion. It appears that a little over 100,000 yd^3/yr of sand must be moving around Point Conception. Bowen and Inman in their classic 1966 littoral sediment budget for the Santa Barbara littoral cell also estimated that approximately 100,000 yd^3/yr of sand enters the cell by longshore transport around Point Conception.

While a minor amount of sand discharged by the Santa

Year	Santa Barbara (cy/yr)	Ventura Harbor (cy/yr)	Channel Islands (cy/yr)	Port Hueneme (cy/yr)
1933	606,400			
1935	202,000			
1938	584,700			
1940	697,700			
1942	600,100			
1945	717,800			
1947	643,000			
1949	838,200			
1952	1,174,000			
1954	1,070,000			
1959	85,100			
1960	522,300		5,335,450	
1961	321,200		0	
1962	269,100		0	
1963	462,900		2,000,000	
1964	368,830	191,000	0	
1965	311,200	180,000	3,526,668	
1966	387,610	143,000	0	
1967	355,285	239,000	0	
1968	385,140	257,000	1,620,000	
1969	274,190	1,883,000	2,824,000	
1970	484,700	325,000	0	
1971	242,820	1,113,000	2,407,000	
1972	401,240	17,000	0	
1973	365,000	1,193,820	2,500,000	
1974	383,300	420,000	0	
1975	46,600	160,000	1,809,523	
1976	395,460	152,000	0	
1977	465,800	911,000	2,370,000	
1978	618,400	496,000	0	
1979	214,800	1,021,500	1,980,244	
1980	310,000	320,000	0	
1981	183,079	812,900	1,522,699	
1982	367,800	1,186,000	0	
1983	405,000	1,427,000	1,260,553	281,718
1984	222,595	1,332,900	0	0
1985	207,466	0	1,850,000	0
1986	292,183	910,000	0	0
1987	223,480	363,100	1,993,956	32,608
1988	112,175	800,000	0	0
1989	134,600	230,314	1,720,000	0
1990	90,281	217,913	0	0
1991	287,781	377,183	1,429,157	199,504
1992	240,500	524,702	0	0
1993	548,823	486,478	1,100,000	0
1994	345,269	470,000	0	0
1995	615,540	271,357	876,666	0
1996	442,347	833,000	0	0
1997	446,819	449,128	1,309,000	0
1998	591,030	741,975	1,638,018	0
1999	376,930	639,173	1,117,406	68,333
2000	376,490	818,477	0	0
2001	261,556	624,931	1,222,934	0
2002	336,375	669,749	0	0
2003	418,088	669,566	2,050,116	0
2004	306,279	578,357	0	0
Average	314,408	596,501	1,010,298	26,462

Maria River may travel upcoast, or northward along the shore, and eventually be lost to the dune complex in the southern region of San Luis Obispo (Everts, 2002), this northward traveling littoral drift is considered to be an insignificant component to the long-term annual sand budget, which has a net southerly littoral drift direction. In addition, sand loads reported for the rivers in this sub-cell may not in fact reach the ocean. There may be losses to the alluvial lowlands or flood plains between the gauging stations and the river mouths; as a result, the calculated river input into the littoral system may be too high. Without a way to quantify the volume of sand lost to the alluvial lowlands and flood plains, which is assumed to be minor, and due to the shoreline configuration and the dominant wave approach from the northwest, we believe a large volume of sand is being lost offshore as it moves around Point Conception (Figures 5.4 and 5.5).

As discussed previously, it has been concluded by many researchers (Azmon, 1960; Bowen and Inman, 1966; Judge, 1970; Trask, 1952) that Point Conception is only a partial barrier to littoral drift. In addition, an offshore geology map developed for the California Division of Mines and Geology (Greene and Kennedy, 1986a,b, 1987a,b, 1989, 1990) using side scan sonar, depicts a large sand deposit ~4.5 miles long and ~1.5 miles wide located ~0.5 miles offshore of Point Conception. If ~470,000 yd^3/yr of sand were lost to this offshore sand bar the accumulation rate (0.07 feet/yr) would result in the sand bar growing in height by ~7 feet over a 100 year period. This is a reasonable scenario, and supports the permanent loss to the littoral budget of a significant amount of sand traveling as littoral drift around Point Conception.

Because of the significance of this probable offshore transport and storage of such a huge volume of beach sand relatively close to shore, in a littoral cell with significant beach sand deficiencies and cliff erosion problems, we strongly recommend that the area offshore from Point Conception be the focus of a detailed multibeam bathymetric study to evaluate the distribution of sea floor sand deposits.

SANTA BARBARA HARBOR TO VENTURA HARBOR

The section of coast from Santa Barbara Harbor to Ventura Harbor does not have many sand sources or sinks. There is only one river contributing sand to this sub-cell, and armored seacliffs back approximately four miles of this shoreline. Sand bypassed from the Santa Barbara harbor introduces an average of ~300,000 yd^3/yr of sand to this reach. This combined with the reported ~100,000 yd^3/yr of sand presently contributed by the Ventura River (Willis et al., 2002), and the negligible amount of sand resulting from seacliff erosion (Runyan and Griggs, 2003), results in total littoral drift of ~400,000 yd^3/yr of sand (Figures 5.4 and 5.5).

The next check-point, Ventura Harbor (Figure 5.6), dredges an average of ~600,000 yd^3/yr (Table 5.2). One factor not yet accounted for, and shown to be an important component to this sub-cell, is long-term beach erosion. Using beach profile comparisons, Noble Consultants (1989) found that the beaches between the Ventura River and the Ventura Harbor have been eroding at a rate equal to approximately 200,000 cubic yards per year. This brings the total longshore transport to ~600,000 cubic yards per year. This balances the average volume of sand, 600,000 cubic yards per year, dredged annually from Ventura Harbor (Table 5.2) (Chang, 2001; 2005; Chang and Evans, 1992; Griggs, 1987b; Wiegel, 1994). Due to the entrance channel configuration at this harbor, the lack of sand accumulation against the downcoast jetty, and the wave protection offered by the Channel Islands, it is probable that for this harbor, net transport is synonymous with gross transport.

It does not appear that a significant amount of sand is moving upcoast and back into Ventura Harbor; although a small groin was built on the downdrift end of this harbor to prevent sand moving upcoast into the harbor entrance (Figure 5.6).

Ventura Harbor, constructed in 1964, is located on an alluvial plain between the Ventura and the Santa Clara rivers (Figure 5.1). Currently, there are seven groins updrift from the harbor entrance, two jetties fixing the entrance to Ventura Harbor, and a detached breakwater, added in 1972, offset and updrift from the harbor entrance. Sand removed when excavating Ventura Harbor was placed between the groins updrift from the harbor (Wiegel, 1994). Similar to Santa Barbara Harbor, upon completion of the Ventura Harbor, sand began to accumulate updrift of the west jetty, and beaches began to erode on the downdrift side. Consequently, the offshore breakwater was built, and a system of dredging in the lee of the breakwater along with sand bypassing was initiated to nourish the downcoast beaches affected by the harbor. Sand is typically discharged onto beaches south of the harbor; however, in the past, dredged material has been placed updrift of the harbor within the groin field (Wiegel, 1994). In recent years however, the cost of re-dredging this sand from Ventura Harbor has eliminated the placement of dredged sand up-drift of the harbor in the groin field.

This rate of littoral drift (~600,000 yd^3/yr) at the Ventura Harbor is consistent with that estimated by Noble Consultants (1989) of ~640,000 yd^3/yr. However, in their analysis, this value includes ~100,000 cubic yards per year of reverse transport emanating from beaches south of Ventura Harbor. Thus, Noble Consultants report a net drift of ~540,000 cubic yards per year, and a gross drift of ~640,000 cubic yards per year. In the present study, the budget appears to be balanced with net and gross drift rates of ~600,000 cubic yards per year to the south.

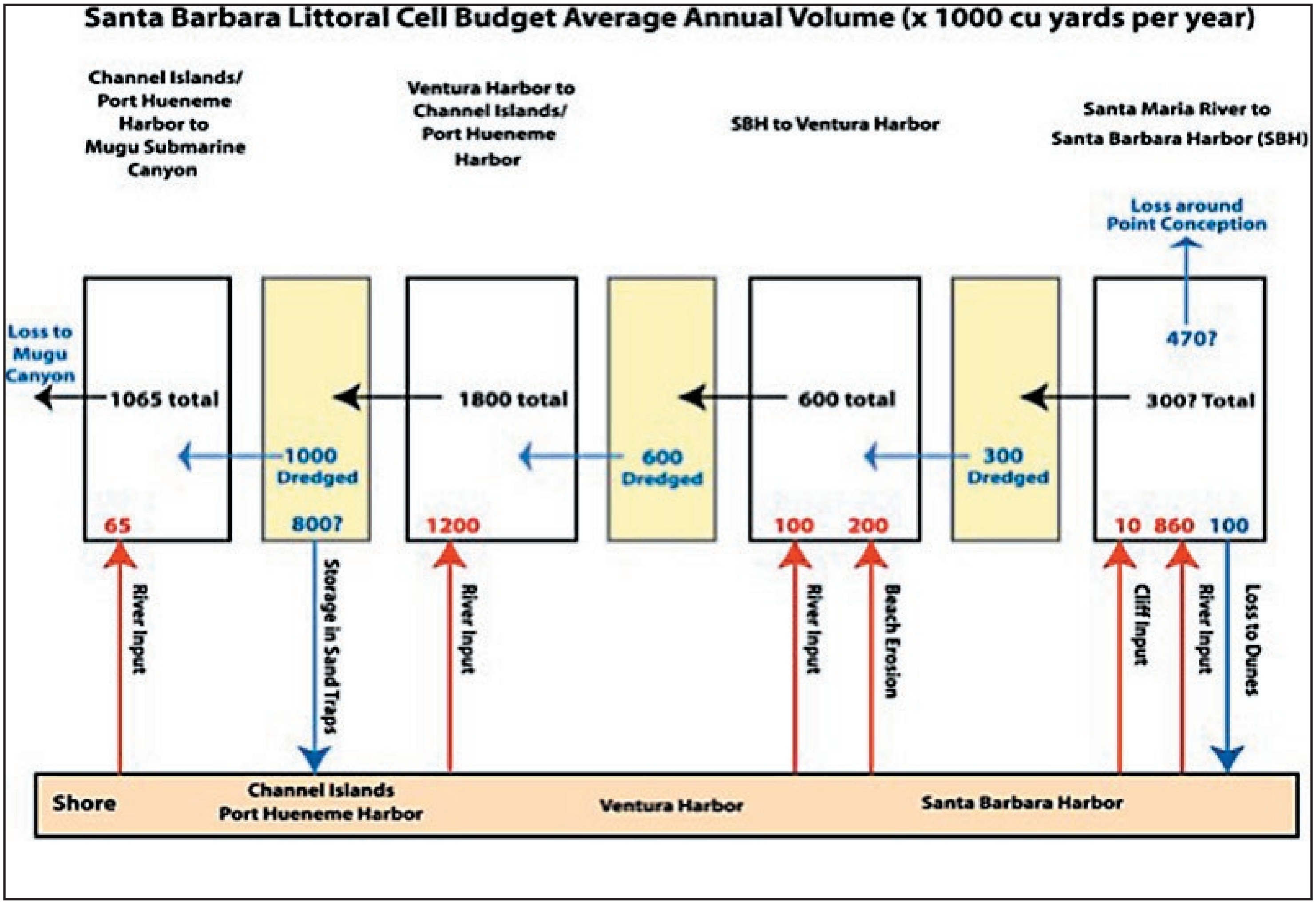

Fig 5.4: Sand Budget for the Santa Barbara Littoral Cell

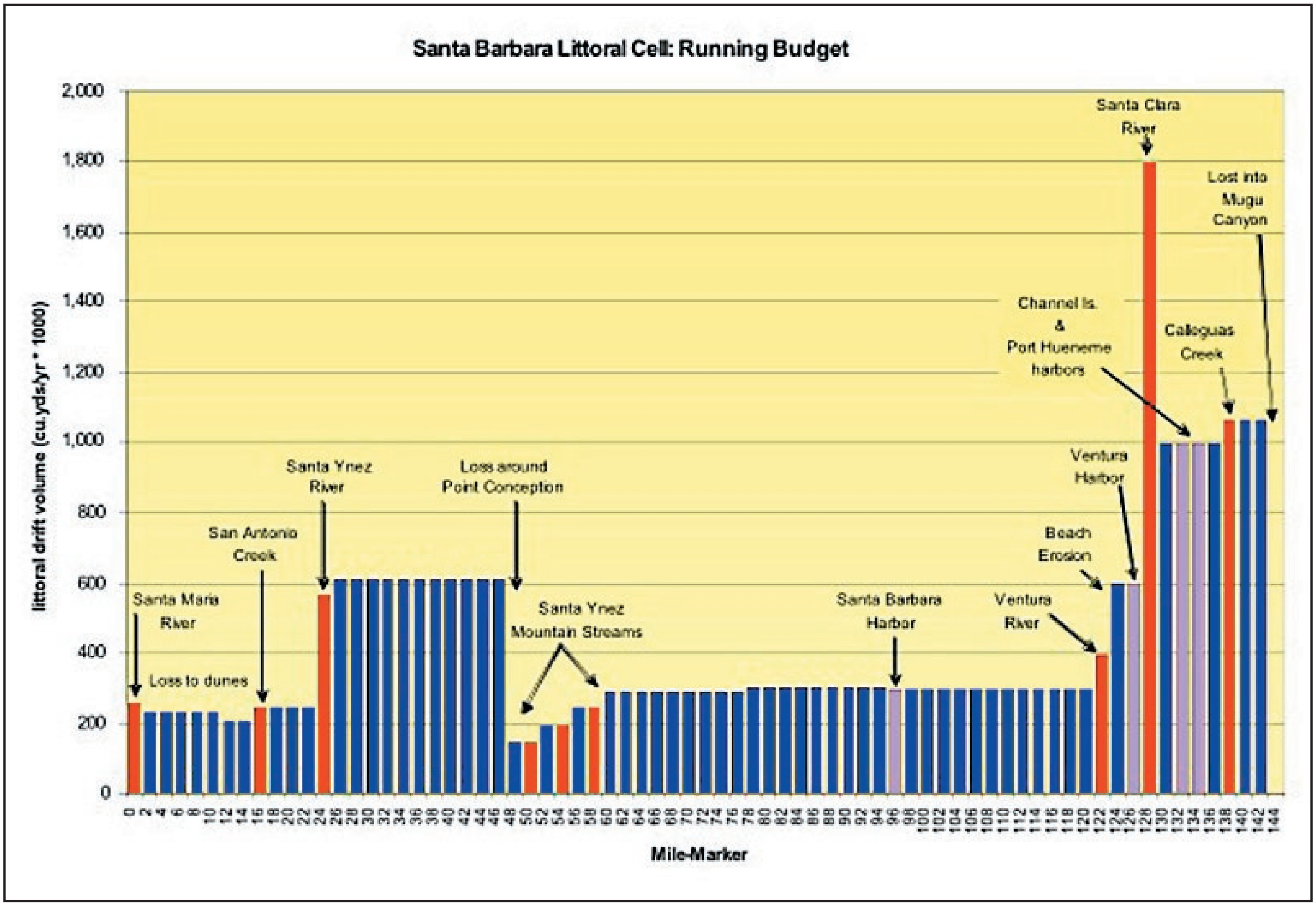

Fig 5.5: Santa Barbara Littoral Cell alongshore, mile-by-mile running sand budget

Fig 5.6: Ventura Harbor: maintenance dredging in 1997

VENTURA HARBOR TO CHANNEL ISLANDS/HUENEME SUBMARINE CANYON

The stretch of coast between Ventura Harbor and Channel Islands Harbor (Figures 5.4 and 5.5) has only one additional source of sand, the Santa Clara River, added to the sand bypassed from the Ventura Harbor traveling along the coast as littoral drift. As previously discussed, approximately 600,000 cubic yards per year of sand is dredged from Ventura Harbor and discharged onto the downdrift beaches. This volume added to the ~1,200,000 cubic yards per year of sand transported by the Santa Clara River (Willis et al., 2002) totals ~1,800,000 cubic yards per year, on average.

Today, Channel Islands and Port Hueneme harbors (Figures 5.7, 5.8 and 5.9) act as a unified sand bypass operation with Silver Strand Beach in between. Port Hueneme Harbor was built in 1940, 20 years before Channel Islands Harbor, as a deep-draft commercial and Navy port. The two jetties stabilizing the entrance to Port Hueneme extend almost to the head of Hueneme Submarine Canyon, which reaches inshore to within 1,000 ft of the beach. Initially, sand moving along the coast as littoral drift was funneled into Hueneme submarine canyon from the updrift entrance jetty, resulting in the calculated loss of ~1.2 million yd^3/yr from the littoral system (Herron et al., 1966). This loss of sand had serious implication to the downdrift beaches.

In an attempt to mitigate the downdrift erosion and to provide additional recreational boat anchorage, Channel Islands Harbor was built in 1960 one-mile updrift from Port Hueneme (Figures 5.7 and 5.8). Sand is dredged from Channel Islands Harbor, pumped under the entrance to Port Hueneme, and is ultimately discharged onto the downdrift beaches. Since its construction, Channel Islands Harbor has been dredged once every two years; with an average dredge volume of ~1,000,000 cubic yards per year. Because Channel Islands Harbor was built primarily as a sand trap to impound and store sand before it was lost into Hueneme Canyon, the amount of annual dredging of this harbor is based on congressional appropriations. Essentially, the amount of sand dredged from the sand trap at Channel Islands harbor is determined by the amount of money left over after the rest of the federally controlled harbors have been dredged to the appropriate navigational depth (typically between 30 and 40 ft). With ~1,800,000 cubic yards per year of sand supplied to this sub-cell and only ~1,000,000 cubic yards per year dredged from Channel Islands Harbor, there appears to be a surplus of sand on the order of ~800,000 cubic yards per year. Again it should be noted that Channel Islands Harbor is not dredged to a consistent depth; thus the average annual dredging volume is only an indicator of the minimum amount of littoral drift moving along this stretch of shoreline. Some of the surplus of sand that appears to exist may be stored in the sand trap at this harbor until there is enough money to dredge it.

The shoreline between the Santa Clara River and the Channel Islands Harbor (including present day Mandalay Beach, Hollywood Beach and the oceanfront residential development at Oxnard Shores) moved seaward from the earliest surveys in the 1850s until the late 1950's and then began to retreat (Inman, 1976). Historical records show that this area was nourished by sand from large floods on the Santa Clara River, and had greater sediment input than waves could remove. This area underwent retreat between 1969 and 1973, however, perhaps a delayed response to diminished littoral drift during the relatively dry years between 1938 and 1969 floods, aggravated by dam construction on the Ventura and Santa Clara rivers (Griggs, Patsch and Savoy, 2005). This may have also reflected changing near-shore bathymetry and wave refraction patterns resulting from the sediments discharged by the large 1969 floods. In the 1990's, however, sand surpluses led to widespread coastal accretion, which encouraged construction of more coastal homes. The calculated excess sand in the budget of the cell at this location may have gone into beach widening over the past 10 or 15 years.

Another possible explanation for this surplus of sand is an overestimation of the volume of sand emanating from the Santa Clara River. Brownlie and Taylor (1981) estimated a sand discharge for this river of ~720,000 yd^3/yr, and Inman earlier (1976) reported a sand volume of ~493,000 yd^3/yr. These two estimates however, did not include the recent El Niño/Southern Oscillation-induced climate cycle, which extended from 1978 until the present. The wet, El Niño period has been shown by Inman and Jenkins (1999) to result in a mean annual suspended sediment flux five times greater than the dry, La Niña climate cycle in the 20 largest streams entering the Pacific Ocean along the central and southern California coast. Willis (2003) used twenty years of additional river discharge data up to the 2001 water year, which is why his estimate of ~1.2 million yd3 of sand annually is greater than previous estimates.

Fig 5.7: Channel Islands and Port Hueneme harbors

Fig 5.8: Channel Islands Harbor dredging, 1979

Similar to the rivers in the first sub-cell, it is possible that all of the sand delivered from this river is not actually reaching the ocean; it may be stored in the alluvial lowlands and delta. However, the gauging station used by Willis (2003) and Brownlie and Taylor (1981) to calculate sand delivery on the Santa Clara is located just three miles from the mouth of the river; it seems improbable that almost 800,000 yds3/yr of sand is being deposited before reaching the ocean.

In addition, the ~1.2 million yd^3 of sand discharged annually reported by Willis and Griggs (2003) includes all sediment coarser than 0.0625mm (4Ø). The littoral cut-off diameter for this cell was determined by Patsch (2004) to be 0.125mm (3Ø). It is possible that a majority of the surplus fluvial sand may be too fine to remain on the beach, and thus, may be lost offshore. It is believed that the inconsistent dredging of Channel Islands Harbor and the use of the sand/silt break instead of the littoral cut-off diameter when assessing the sand contribution of the Santa Clara River may account for much of the apparent surplus of sand in this sub-cell (Figures 5.4 and 5.5). Additional sand has also been stored along the five miles of beach between the Santa Clara River and the Channel Islands Harbor as this area has accreted over the past 15 years. More research is recommended to determine the extent of beach accretion along this five-mile stretch of coast.

Due to the effective sand-bypass system at Channel Islands Harbor, which pumps most of the sand dredged from the harbor to the beach south of Port Hueneme (Hueneme Beach), very little sand is now lost into Hueneme Submarine Canyon. When dredging Channel Islands Harbor, approximately 5% to 10% of the sand is placed on Silver Strand Beach, between Channel Islands Harbor and Port Hueneme, to maintain the beach. This sand is eventually lost into Hueneme Submarine Canyon.

Fig 5.9: Port Hueneme Harbor, 1979

HUENEME SUBMARINE CANYON TO MUGU SUBMARINE CANYON

Between Port Hueneme Harbor and the Mugu submarine canyon, Calleguas Creek is the only source of sand and it supplies this sub-cell with ~65,000 yds3/yr of sand. Added to the ~1,000,000 yds^3/yr of sand bypassed from the updrift harbors moving downcoast as littoral drift, this sub-cell has a surplus of sand on the order of ~1,065,000 yds^3/yr (Figures 5.4 and 5.5). The beaches between Port Hueneme Harbor and Mugu canyon appear to be in a state of dynamic equilibrium, neither narrowing or accreting in recent years; thus, it is concluded that the ~1,065,000 yds^3/yr of sand on average is lost into the Mugu Submarine Canyon, which extends into the surf zone, terminating the Santa Barbara littoral cell. This conclusion is in agreement with Bailard's (1985), Inman's (1976), and Everts and Eldon's (2005) estimates of sand lost into Mugu Submarine Canyon.

SUMMARY OF THE SANTA BARBARA LITTORAL CELL SAND BUDGET

The sand budget for the Santa Barbara Littoral Cell can be depicted as both a simplified box model (Figure 5.4) and also as a shows the cumulative, mile-by-mile, transport of the "river" of sand (Figure 5.5). This cell appears to be in a general state of dynamic equilibrium, with enough sand supplied by the rivers and bypassing operations to feed the beaches of the cell. Sand does appear to be eroding from the beaches, however, between Santa Barbara and Ventura harbors. Seacliff erosion has been shown to provide a negligible amount of sand (Runyan and Griggs, 2003; Runyan and Griggs, 2002); thus, any sand management plans should focus efforts on sand resources from the rivers and streams in this littoral cell, not seacliff erosion. Overall, sand supply to the Santa Barbara littoral cell has been reduced by 40.4% or ~1,479,000 yd^3/yr (~1,476,000 yd^3/yr from the damming of rivers and ~3,000 yd3/yr from the armoring of seacliffs).

There are a few areas of localized beach erosion (Noble Consultants, 1989); however, it is unclear at this point whether this is long-term beach erosion resulting from a reduction in sand supply, or if the observed erosion is the seasonal fluctuation in beach width which has been far more pronounced over the past two decades due to more prevalent and severe El Niño events (Storlazzi and Griggs, 2000; Dave Revell, personal communication).

Three harbors act as constraints or check-points for the littoral drift in this cell. Based on the dredging history over the last 70 years, the longshore drift rates at the Santa Barbara, Ventura, and Channel Islands/ Port Hueneme Harbors are: ~300,000 cubic yards per year, ~600,000 cubic yards per year, and a minimum of ~1,000,000 cubic yards per year respectively (Table 5.2). Given the unidirectional southeastward movement of littoral drift in this cell, the entrance channel configurations of the harbors themselves and the lack of significant sand accumulation on the downcoast jetties, the southeastward trending Santa Barbara Channel, and the dominant angle of storm wave approach from the northwest, reverse transport is believed to be negligible, and these rates are believed to represent both the net and gross longshore transport rates.

Chapter 6

SANTA MONICA LITTORAL CELL SAND BUDGET

The Santa Monica littoral cell extends 57 miles from Point Mugu near the Mugu Submarine Canyon on the west to Palos Verdes Peninsula on the southeast and includes Santa Monica Bay (Figure 6.1). The beaches of Santa Monica Bay encompass a 36-mile arc from Point Dume (Figure 6.2) on the northwest to Malaga Cove on the southeast, and typically host more than 50 million visitors every year. This stretch of coast, located adjacent to the Los Angeles metropolitan area, also provides innumerable recreational activities including surfing, swimming, hiking, fishing, volleyball, and sunbathing. The beaches in this littoral cell are one of the most important "natural" resources in this region; however, very little sand presently enters this cell to naturally maintain the beaches. The sand budget for the Santa Monica littoral cell is one that has been marked by significant human intervention.

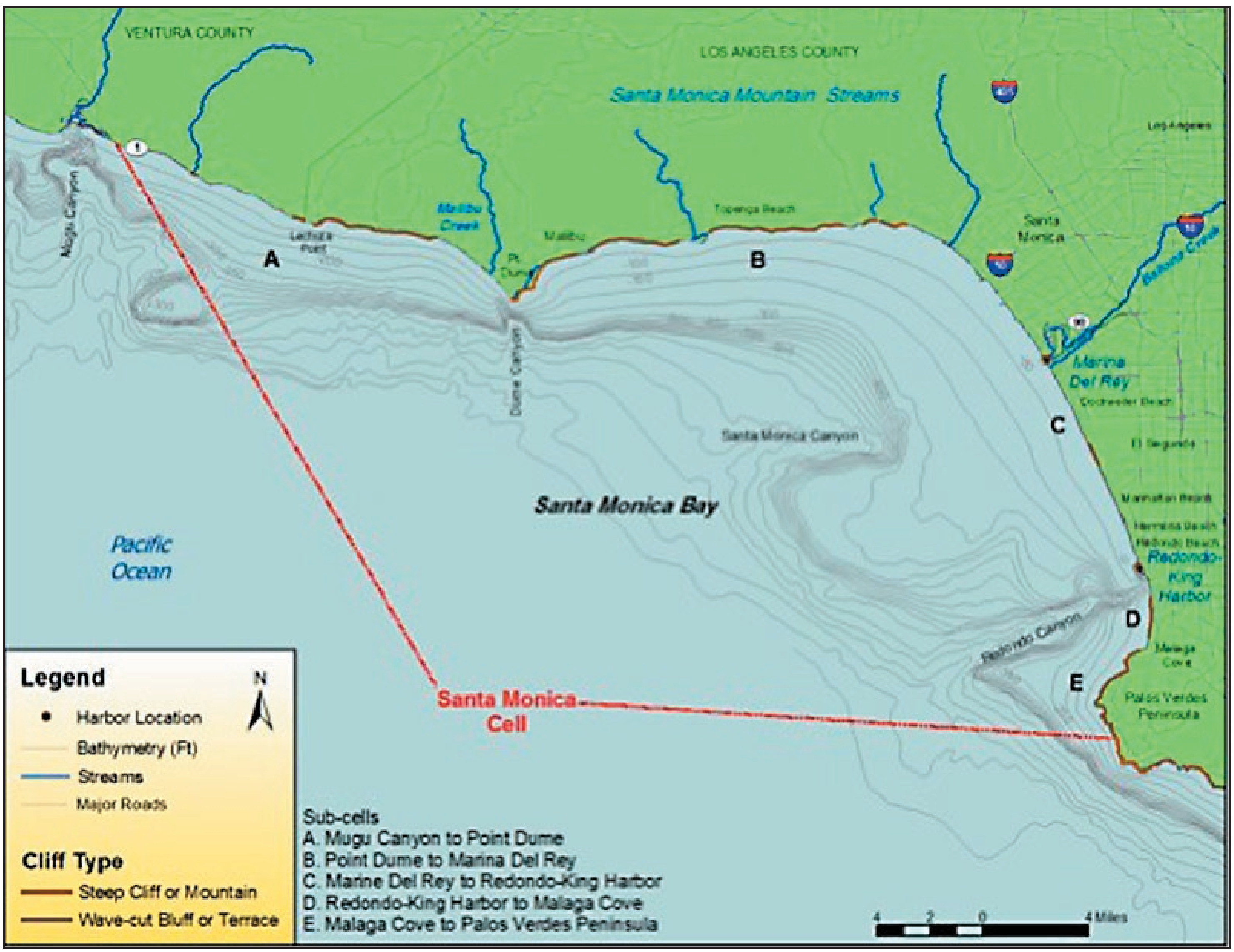

Fig 6.1: Map of the Santa Monica Littoral Cell

For the past 65 years, the beaches in the central and southern portion of Santa Monica Bay have been artificially nourished with sand to provide wide, stable beaches for residents and visitors and also to create a natural buffer from wave attack (Figure 6.3). These beaches are typically 150- to 500-feet wider than the naturally occurring beaches (Leidersdorf et al., 1994). In the northern portion of the cell, from Point Mugu to Malibu, beach nourishment has not been regularly implemented, and, as a result, the natural beaches remain quite narrow (Figure 6.4).

Numerous shoreline engineering structures have been built in this cell in an attempt to retain sand on the beaches, especially where the beaches were artificially nourished. These structures have ultimately compartmentalized the shoreline, reduced alongshore transport,

Fig 6.2: Point Dume. Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 6.3: Beaches in the central and southern portion of the Santa Monica Cell are wide, stable, and artificially nourished (Dockweiler State Beach). Copyright © 2002 Kenneth & Gabrielle Adelman

and minimized the amount of sand lost into the main sink of this cell, Redondo Submarine Canyon. Overall, human intervention, consisting of beach nourishment and the construction of structures, has been successful in creating wide, stable beaches in the central and southern portion of the Santa Monica littoral (Flick, 1993; Herron, 1980; Leidersdorf et al., 1994).

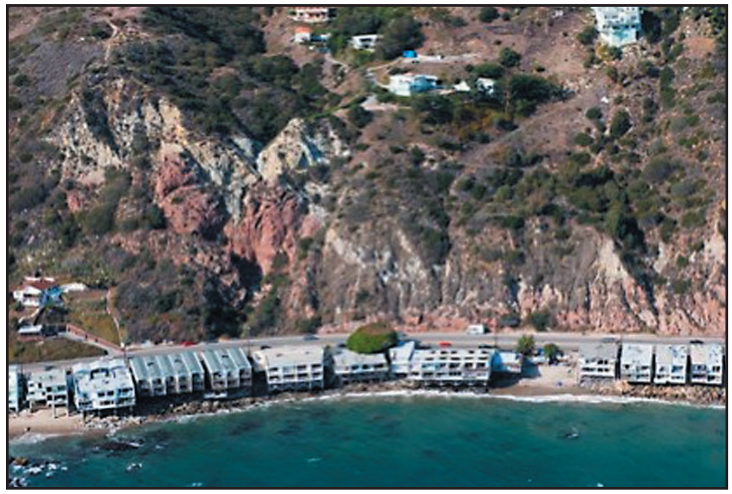

Fig 6.4: Beaches in the northern portion of the Santa Monica cell are not nourished and are naturally narrow (Malibu). Copyright © 2004 Kenneth & Gabrielle Adelman

LONGSHORE TRANSPORT AND THE NATURAL STATE OF THE BEACHES

In their natural condition, the beaches in the Santa Monica cell are quite narrow due to the lack of significant sand sources, high rates of longshore or littoral transport, and the natural loss of sand into Dume and Redondo submarine canyons. Waves enter Santa Monica Bay predominantly from the west resulting in a net transport of sand toward the south and east from Mugu Canyon towards Redondo Submarine Canyon (Leidersdorf et al., 1994). Transport reversals do occur, typically during summer south swell events; however, it has been estimated that the southerly transport rate in the Santa Monica region is seven times greater than the northerly transport (USACOE, 1986). Using the accumulation of sand at coastal structures, Hadin (1951) estimated longshore transport to be ~270,000 yd^3/yr at Santa Monica Beach and ~162,000 yd^3/yr at El Segundo Beach. More recent estimates of littoral drift vary from 190,000 yd^3/yr (Engineers, 1992; USACOE, 1994) to 400,000 yd^3/yr (USACOE, 1994). The earlier rates of littoral drift may represent a time when sand supply did not meet the potential longshore transport. As more sand was added to the system through beach nourishment as well as an increase in sand supply and wave energy due to El Niño events (increased sediment discharge from the coastal streams as well as the potential for increased coastal bluff erosion), waves were able to carry the additional sand downcoast thus increasing the estimated longshore transport.

The curvature of Santa Monica Bay south of Redondo Beach and Submarine Canyon produces a net transport of littoral drift to the north (Jones, 1947). Thus, from the northern point in the cell, littoral drift, uninterrupted, will travel south and east until it is eventually lost into

Redondo canyon, and from the southern point in the cell, littoral drift will travel north until it is also lost into Redondo Canyon.

Redondo Submarine Canyon is the confluence of the southern and northern trending alongshore transport of sand established in the Santa Monica littoral cell. With its head located within 200 yards of the shoreline, Redondo Submarine Canyon serves as an effective sink for this cell. Today, due to the extensive compartmentalization of the shoreline in Santa Monica Bay, little sand is lost into the canyon. Before human intervention, it was estimated that 200,000 to 400,000 yd^3/yr of sand ended up in Redondo Submarine Canyon (Gorsline, 1958).

STRUCTURES

As of 1990, there were 5 shore-parallel breakwaters, 3 shore-normal jetties, 19 groins, 6 open-pile piers, and 2 harbors in the 21.6-mile stretch of coast between Topanga Beach and Malaga Cove (Corporation, 1992; Leidersdorf et al., 1994; Wiegel, 1994). Locations for these structures are listed in Table 6.1. The groins and jetties extending perpendicular to the coast interrupt the longshore current inhibiting the movement of sand traveling alongshore as littoral drift, thus compartmentalizing the shoreline and creating sub-cells within the larger Santa Monica littoral cell. Due to the unidirectional net transport direction in most of this littoral cell, groins are exceptionally successful at trapping sand and maintaining the beaches (Flick, 1993).

Harbors	Breakwaters (5)	Piers (6)	Jetties (3)	Groins (19)
Marina del Rey	Santa Monica (1)	Santa Monica (1)	Marine del Rey (2)	Sub cell B (12)
Redondo/King	Venice (1)	Venice (1)	Ballona Creek (1)	Sub cell C (5)
Harbor	Marine del Rey (1)	Manhattan		Sub cell D (2)
	Redondo (2)	Hermose		
		Horseshoe (Redondo)		
		Monstad (Redondo)		

Table 6.1: Summary of coastal structures on the beaches of Santa Monica Bay: Topanga Beach to Malaga Cove. Subcells: B. Point Dume to Marina del Rey; C. Marina del Rey to King Harbor; D. King Harbor to Malaga Cove. Source: County of Los Angeles, 1990 in Coastal Frontiers Corporation, 1992

SAND SOURCES AND SINKS

Rivers: Rivers typically provide the majority of sand to littoral cells in California (Brownlie and Taylor, 1981; Inman and Frautschy, 1966); however, this is not the case for the Santa Monica cell. The most important historic event impacting the sand budget for the Santa Monica littoral cell was the change in the course of Los Angeles River. Prior to 1825, the Los Angeles River discharged through Ballona Creek providing a substantial amount of sand to this cell. However, in 1825, unusually heavy flooding caused the river to change its course and discharge into San Pedro Bay, approximately 26 miles southeast of its original outlet (Handin, 1951; Kenyon, 1951; Knur and Kim, 1999; Wiegel, 1994). Thus, for over a century the Santa Monica littoral cell has lacked a major natural source of sand.

Ballona Creek, Malibu Creek, and the Santa Monica Mountains' streams contribute a minor volume of sand to this cell. Willis and Griggs (2003), using up-to-date stream discharge information, determined that Ballona Creek, a small ephemeral stream, delivers ~3,000 yd^3/yr of sand annually, and the Santa Monica Mountains' streams cumulatively discharge ~43,000 yd^3/yr of sand. Today, Malibu Creek contributes ~24,000 yd^3/yr of sand annually on average. This is a reduction of 55% from the natural sand discharge due to the damming and control of Malibu Creek (Knur and Kim, 1999; Willis and Griggs, 2003). Thus, streams contribute a total of ~70,000 yd^3/yr of sand to the Santa Monica littoral cell on average, which is a total reduction of 30%, or 29,300 yd^3/yr, due to the damming of Malibu Creek (Table 6.2). However, this is an over-estimation of the volume of sand that will actually remain on the subaerial beaches of the cell. The volume of sand represented by these numbers is sand that is coarser than 4Ø (0.0625mm), or the sand/silt break on the commonly used Wentworth Scale. The littoral-cut-off-diameter, which is the smallest grain-size of sediment that will remain on the beaches, for this cell was determined to be 3Ø (0.125mm). The grain-size data on sediment discharged by these streams, which is necessary to discern the percentage of sediment sufficiently coarse to remain on the beaches and in the littoral system, is not available.

Bluff Erosion: Seacliffs and bluffs constitute 17 miles of the shoreline in the Santa Monica littoral cell (Figure 6.1). Using factors such as alongshore cliff length, cliff or bluff height, terrace deposit thickness, grain size of cliff or bluff and terrace deposit materials, erosion rate, and littoral-cut-off diameter, bluff erosion was determined to contribute a minimal amount of sand to this littoral cell. Although bluff erosion is not contributing much sand to the littoral budget, it does constitute 60% of the "natural" and 23% of the "actual" sand supplied to this cell (Table 6.2).

With the lack of a large sand contribution from rivers or streams, the role of bluff erosion in contributing sand to the beaches in this cell is increased. Overall, erosion of coastal bluffs contributes an average of ~150,000 yd^3/yr of beach-sand-sized material (coarser than 3Ø or .125mm). Nearly 9,000 feet of bluff armoring have reduced the historic, or natural, volume by only 1% (~2,000 yd^3/yr; Table 6.2). Most of this sand (~133,000 yd^3/yr), however, is emanating from the stretch of coast from Malaga cove to Palos Verdes Peninsula where it travels north and is lost into the Redondo Submarine

Canyon, providing little to no sand to beaches in the northern and central stretches of this cell.

Santa Monica Littoral Cell			
Inputs	Natural Sand (yd^3/yr)	Actual Sand Yield (yd^3/yr)	Reduction (yd^3/yr)
Rivers Bluff Erosion Beach Nourishment	100,000 (40%) 150,000 (60%) 0 (0%)	70,000 (11%) 148,000 (23%) 428,000* (66%)	30,000 (30%) 2,000 (1%) +428,000
Total Littoral Input	250,000 (100%)	646,000 (100%)	-396,000 (+158%)

Table 6.2: Over-all sand contributions and reductions to the Santa Monica littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment. The natural and actual sand yield from bluffs is taken after the construction of the Pacific Coast Highway in 1926.

*Average annual beach nourishment is taken between 1926 and 2004.

Beach Nourishment: Over the last 65 years, beach nourishment has been the main source of sand for the Santa Monica littoral cell, overshadowing the amount of sand supplied by the rivers and bluff erosion. Leidersdorf et al. (1994) estimate that ~33 million yd^3 of sand have been placed on the beaches of the Santa Monica littoral cell over a 60 year span, which averages out to be ~550,000 yd^3/yr. This is consistent with the estimate made by Flick (1993) of 30 million yd^3 of sand over a 50-year span (or ~600,000 yd^3/yr) placed on the beaches in this cell. However, since 1970, beach nourishment has significantly decreased. Leidersdorf et al. (1994) determined that only 1.7 million cubic yards (~70,000 yd^3/yr) was added to the beaches between 1970 and 1994, in contrast to the 29.8 million yd^3 (~1 million yd^3/yr) added from 1938 to 1969. Leidersdorf et al (1994) attribute the decrease in nourishment to the following: 1. a decrease in construction projects along the coast; 2. more stringent regulations and standards for the size and quality of acceptable sand used for nourishment; and 3. the relative stability of earlier fill as a result of retention structures.

Some of the largest opportunistic beach nourishment projects came along with the construction and expansion of the Hyperion Sewage Treatment Facility inland of Dockweiler Beach and the construction of the Pacific Coast Highway. From 1938-1989 ~17 million cubic yards of sand were added to the beaches between Santa Monica and El Segundo as a result of the construction and expansion of the Hyperion Sewage Treatment Facility. From 1946 to 1948 ~14 million cubic yards of sand were excavated from coastal sand dunes during construction of the Hyperion Facility, and disposed of along a 7-mile stretch of beach from the Santa Monica Pier to El Segundo Beach widening the beaches by an average of 600 feet (Leidersdorf et al., 1994; Wiegel, 1994). Prior to this, in 1938, 1.8 million cubic yards of sand were excavated from the sand dunes at the future site of the Hyperion Facility in anticipation of construction and placed on the beach (Wiegel 1994). One of the most recent beach nourishment projects associated with Hyperion occurred in 1989 when 1.1 million yds^3 of sand were transported by conveyor belt from Hyperion, across Pacific Coast Highway, and deposited on Dockweiler beach (Flick, 1993).

The construction and maintenance of the Pacific Coast Highway has also provided a large volume of sand to this littoral cell. Large cuts, ranging in height from 20 to 60 feet, were made into the hillside of the Santa Monica Mountains to build the highway. The largest cuts were made between Point Mugu and Little Sycamore Canyon six miles to the southeast (Knur and Kim, 1999). The highways fills were not armored until the 1960's. Knur and Kim (1999) estimate 1.2 million cubic yards of sand were used as beach nourishment from the initial construction of the highway, with another ~150,000 cubic yards of sand from the subsequent maintenance to the highway. Thus, ~1.35 million cubic yards of sand was added to the budget of the Santa Monica littoral cell due to the construction and maintenance of the Pacific Coast Highway since 1926. However, in locations where the highway was built between the mountains or bluffs and the ocean, bluff erosion was eliminated as a long-term source of sand. Because of the location of the highway, only 65% of the bluffs along the Malibu coastline are capable of contributing sand (Knur and Kim, 1999).

Submarine Canyons: Dume Submarine Canyon is located offshore of Point Dume (Figures 6.1 and 6.2). The mouth of Dume canyon reaches to within 800 feet of the shoreline and descends to a depth of over 2,000 feet (Knur and Kim, 1999). Most researchers agree that Point Dume and Dume Submarine Canyon act as partial barriers to littoral drift; however, they do not agree on the volume of sand successfully making its way around the promontory and the volume of sand lost into Dume Submarine Canyon (Inman, 1986; Knur and Kim, 1999; Orme, 1991).

Inman (1986) reports that during moderate wave conditions, 90% of the material traveling as littoral drift southward towards Point Dume is transported around the promontory, bypassing the canyon head. Orme (1991), however, concluded the converse, that only 10% of littoral sediments bypass the point and canyon mouth. Knur and Kim (1999) attempted to resolve this discrepancy by performing their own analysis. They analyzed bathymetric contours from a survey conducted by the U.S. Army Corps of Engineers (1950), and calculated a "depth of closure" ("depth of closure" is defined as the depth beyond which no significant seasonal transport or movement of littoral sand takes place) by using an equation from the U.S. Army Corps of Engineers' Shore Protection Manual (1984). Assuming that sand transport occurs at an equal rate throughout the zone of transport from the shore to the depth of closure, Knur and Kim found that 70% of littoral drift enters Dume Submarine Canyon, and is effectively removed from the littoral cell budget. Thus, only 30% of the littoral sand bypass Point Dume and Dume Submarine Canyon (Knur and Kim 1999).

Santa Monica Submarine Canyon lies between Dume and Redondo canyons (Figure 6.1) but the canyon head lies about 7 miles offshore near the shelf break so is not a sink for modern littoral sand.

As discussed earlier, Redondo Submarine Canyon is located just offshore of King Harbor in the southern portion of Santa Monica Bay (Figure 6.1). With its head located within 200 yards of the shoreline near the end of the King Harbor breakwater, sand is essentially funneled into Redondo Submarine Canyon, effectively removing it from the sand budget for this cell. Today, due to the extensive compartmentalization of the shoreline in Santa Monica Bay, little sand is actually lost into the canyon. Before human intervention Gorsline (1958) estimated that 200,000 to 400,000 yds3 of littoral sediments per year were lost into the canyon. Retentions structures such as groins have trapped littoral drift, allowing this sand to remain on the beaches.

On- and Off-Shore Transport: Cross-shore transport can potentially be an important sand source or sink for a littoral cell. This component, however, is very difficult to quantify. It has been assumed by many researchers (Best and Griggs, 1991b; Best and Griggs, 1991a; Knur and Kim, 1999; Komar, 1996) that on- and off-shore transport will essentially balance over time, and it is negligible in consideration of the large volumes of sand in a large-scale, long-term littoral cell sand budget. Cross-shore transport of sand has not been quantified by any researchers for the Santa Monica littoral cell, and has not been attempted in this study. High-resolution multibeam bathymetry can delineate seasonal changes in sediment distribution or thickness on the inner shelf or beyond the depth of closure as has been seen off Santa Cruz (Storlazzi, USGS, personal communication).

To date, however, these high resolution bathymetric studies have not been systematic or frequent enough, or combined with bottom current measurements, such that seasonal on- or off-shore net sand transport can be confirmed. Because of the potential importance of this transport and the volumes of sand involved, several such studies are recommended in areas where such cross-shore transport may be significant to balancing the littoral budget (southern Monterey Bay, for example).

SUMMARY OF THE SAND BUDGET FOR THE SANTA MONICA LITTORAL CELL

A. Point Mugu to Point Dume: Point Mugu (Figure 6.5) and the Mugu Submarine Canyon mark the termination of the Santa Barbara littoral cell and the beginning of the Santa Monica littoral cell. Mugu canyon is an effective littoral trap such that little to no sand is transported from one cell to the other. Just over 5.6 miles of the nine-mile stretch of coast from Point Mugu to Point Dume consist of bluffs interrupted by small pocket beaches. Bluff erosion was found to contribute an average of 8,000 yd^3/yr of sand to this sub-cell. The sand contribution has been reduced by approximately 12% (~1,000 yd^3/yr) from the natural contribution due to the armoring of ~3,500 feet of bluffs in this stretch of coast. No beach nourishment has taken place in this sub-cell (Wiegel, 1994).

Fig 6.5: Point Mugu. Copyright © 2002 Kenneth & Gabrielle Adelman

B. The Malibu Coastline: Point Dume to Marina del Rey: The 26 mile-long stretch of coast from Point Dume to Santa Monica Canyon in the western Santa Monica Mountains is marked by pocket beaches bounded by rocky headlands and narrow, sand-starved beaches.

The Santa Monica Mountains are an east-west trending range about 50 miles long and 9 miles wide with an elevation range from sea-level to over 3,000 feet. The mountains are generally steep-sided with narrow valleys. Rainfall in the Santa Monica Mountains occurs primarily between November and April, with the largest sediment producing storms occurring between December and February (Knur and Kim, 1999). Bluff erosion was found to contribute an average of ~5,000 yd3/yr of sand to the beaches in this sub-cell, which is a reduction of ~900 yd^3/yr (or 18%) due to bluff armoring.

The coastline of the Santa Monica Mountains is characterized by numerous pocket beaches that are bounded by headlands. These headlands result from the high erosional resistance of the bedrock in comparison with the surrounding materials. Resistant headlands include

Sequit Point, Point Dume, and Latigo Point. Headlands are also formed from deltaic deposits, or cobbles and boulders, found at the mouths of streams, which are too large to be moved by the littoral currents, and effectively interrupt littoral drift, much like a shore-perpendicular structure such as a groin. Such headlands occur at Malibu Point, Las Flores Point, and Topanga Point. Most of the pocket beaches are a few hundred yards in length with the exception of Zuma Beach, which is just over four miles long (Knur and Kim, 1999).

Development began in the Santa Monica Mountains in the 1880's. With the construction of dams for irrigation and recreation, and the placement of coastal engineering structures to protect homes and public facilities, the amount of sand reaching the coast in this sub-cell has diminished. Dam construction began in 1881, and by the late 1920's the largest of the dams were constructed. By the 1970's, a total of 22 dams interrupted the flow of water through the streams in the Santa Monica Mountains (Knur and Kim, 1999; Willis and Griggs, 2003; Willis et al., 2002).

Many of these coastal dams, such as the 100-foot-high Rindge Dam on Malibu Creek, are completely filled with sediment, and are no longer providing any value. Rindge Dam, built in 1926, completely filled its 574 acre-foot reservoir in the first 25 years after construction. It is estimated that between 800,000 and 1.6 million cubic yards of sediment is currently stored behind the dam. The U.S. Army Corps of Engineers and California State Parks have undertaken a feasibility study on the removal of Rindge Dam to help restore Malibu Creek's natural sediment supply. Thus far, cost estimates for the removal of Rindge Dam are between $4 million and $18 million, depending on the strategy of sediment removal.

Beginning around 1926, development began on the south side of the Santa Monica Mountains, aided by the construction of Pacific Coast Highway through Malibu. In order to build the highway, large sections of the hillside had to be removed. As previously discussed, ~1.35 million cubic yards of sand from these excavations were placed on the beaches as nourishment (Knur and Kim, 1999). From Point Dume to Will Rogers State Beach, along the Malibu shoreline, the sand-starved beaches are narrow and remain close to their natural state. From 1923-1958, 33 groins were built along the Topanga Beach/Will Rogers section of the coast, many of which have now either been destroyed or buried (Shaw, 1980; Wiegel, 1994; Woodell and Hollar, 1991). Will Rogers State Beach currently has an extensive groin field consisting of at least 8 groins to compartmentalize the shoreline; however, the beaches remain narrow at the updrift ends of the structures because no nourishment activity accompanied the construction of the groins.

The Santa Monica Municipal Pier and the adjacent wide, sandy beach is an extremely popular tourist destination (Figure 6.6). The wide beach is a result of a 2,300-foot-long detached breakwater, built in 1934, just north of the pier and 2,000 ft offshore, to create the Santa Monica Harbor (Wiegel, 1994). Immediately after construction of the breakwater, substantial accretion occurred in lee of the structure that extended southward past the pier The beach width increased by over 650 feet at a distance of one mile upcoast from the structure (Flick, 1993). Farther downcoast severe beach erosion occurred. Storms associated with the El Niño winter of 1982/1983 damaged the top of the Santa Monica breakwater, lowering it to -6ft (MLLW), and allowing for natural alongshore transport to partially resume (Leidersdorf et al., 1993; Wiegel, 1994).

Venice Breakwater, a detached, shore-parallel, rubble-mound structure built in 1905, is located approximately two miles south of the Santa Monica Pier, and is often connected to the shoreline by a tombolo (Figure 6.7), creating a littoral barrier. This structure is 600-ft long and is located 1,200 ft offshore. Once again, the beaches in this area have historically been maintained by beach nourishment, and have also benefited from the construction of Marina del Rey's northern jetty. Venice Beach was nourished with 150,000 cubic yards of sand in 1945 and some portion of the 13.9 million cubic yards of sand placed on Dockweiler and Venice beaches from the construction and maintenance of the Hyperion Sewage Treatment Facility (Table 6.3) (Leidersdorf et al., 1994).

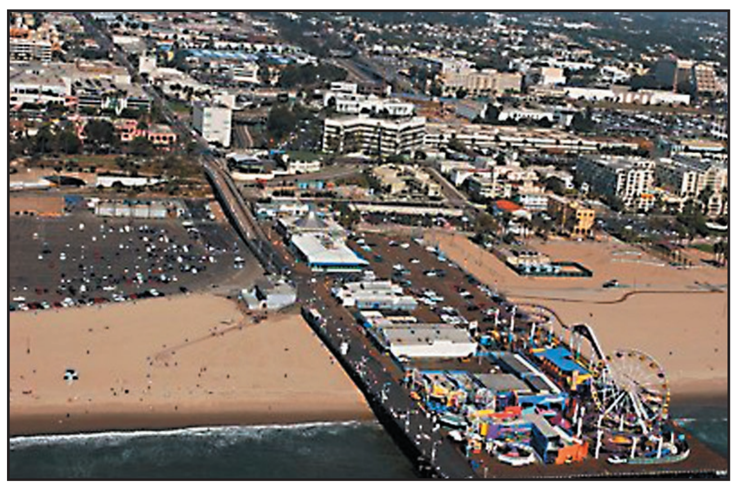

Fig 6.6. Santa Monica Municipal Pier. Copyright © 2002 Kenneth & Gabrielle Adelman

Marina del Rey (Figure 6.8), located 15 miles southwest of Los Angeles, is one of the largest man-made recreational boating and residential marinas in the world with over 6,000 moorings for boats and facilities for thousands more. In the early 1960's, Marina del Rey was constructed by dredging the wetlands of Ballona Lagoon in order to meet the demands of a rapidly growing population in the Los Angeles region. Designed by the U.S. Army Corps of Engineers, the original jetties stabilizing the entrance to the marina were inadequate.

Date	Sub-Cell	Placement Location	Source of Material	Purpose	Quantity (yd^3)	Source
1926+	B	Unknown	PCH construction	Disposal	1,350,000	Knur & Kim (1999)
1938	C	Dockweiler Beach	Hyperion	Disposal	1,800,000	Leidersdorf et al (1994)
1945	B	Venice Beach	Hyperion	Disposal	150,000	Leidersdorf et al (1994)
1947	B/C	Venice/Dockweiler	Hyperion	Disposal	13,900,000	Leidersdorf et al (1994)
1947	D	King Harbor to Malago Cove			220,000	Wiegel (1994)
1947	D	Redondo Beach	Onshore	Nourishment	100,000	Leidersdorf et al (1994)
1956	C	Dockweiler Beach	Scattergood	Disposal	2,400,000	Leidersdorf et al (1994)
1960-62	C	Dockweiler Beach	Marina del Rey	Disposal	3,200,000	Leidersdorf et al (1994)
1962	D	King Harbor to Malago Cove			220,000	Wiegel (1994)
1963	C	Dockweiler Beach	Marina del Rey	Disposal	6,900,000	Leidersdorf et al (1994)
1968-69	D	Topaz St. Groin to Malago Cove	Offshore	Nourishment	1,400,000	Wiegel (1994); Leidersdorf et al (1994)
1984	C	El Segundo	Offshore	Nourishment	620,000	Leidersdorf et al (1994)
1988	C	Dockweiler Beach	Hyperion	Disposal	155,000	Leidersdorf et al (1994)
1988-89	C	El Segundo	Hyperion	Disposal	945,000	Leidersdorf et al (1994)

Table 6.3: Beach Nourishment Projects in the Santa Monica littoral cell

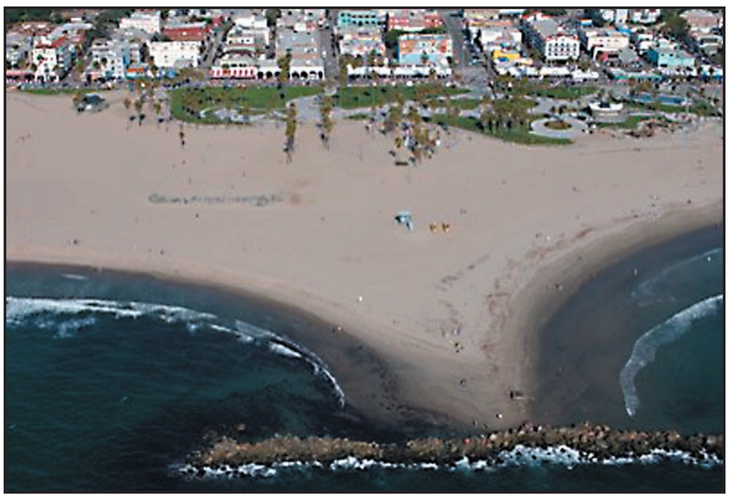

Fig 6.7: Tombolo formation behind the Venice breakwater upcoast from Marina Del Rey Harbor. Copyright © 2004 Kenneth & Gabrielle Adelman

The jetties were intended to dissipate wave energy inside of the marina. However, after their construction and the inhabitation of the marina by boaters, waves as high as six feet began to set up resonance patterns within the entrance channel and traveled into the marina causing extensive damage to boats and facilities. Some boat-owners abandoned Marina del Rey and venders sued Los Angeles County for lost revenue (Griggs et al., 2005).

The first response to this problem was to install temporary baffles across and within the main channel to prevent waves from entering the harbor. Eventually, after a large-scale modeling effort was completed, a 1,200-foot, detached breakwater was constructed just offshore of and across the ends of the jetties thus creating a safe haven for the boats within the marina.

The construction of the breakwater, although successful in creating a safe harbor, interrupted littoral drift, and created a navigational hazard in the southern approach to the inlet due to shoaling from the deposition of sand by Ballona Creek adjacent to the south jetty (Griggs et al., 2005).

Fig 6.8: Marina Del Rey and Ballona Creek (1989) Copyright © 2004 Kenneth & Gabrielle Adelman

Dredging of the entrance channel to a minimum depth of 18 feet was initiated in 1969 to maintain a safe navigational channel into the marina (Table 6.4). Although most of this dredged material has been bypassed and used at a source of beach nourishment for the down-coast beaches, often the sand is too contaminated to be placed directly on the downdrift beaches. From 1969 to 2001, 2.2 million yd^3 (or 62,500 yd^3/yr) of sand was dredged from Marina del Rey and placed on the down drift beaches as opportunistic beach nourishment (Table 6.4).

Two ~650-foot-long, rubble-mound jetties were constructed in 1938 to stabilize the Ballona Creek outlet (Figure 6.8). In 1946, the jetties were extended 590 feet causing significant erosion downdrift. In 1956, 2.4

Year	Quantity (yd^3)	Source	Placement
1939	60,000	Santa Monica Breakwater	Santa Monica Beach
1949	960,000	Santa Monica Breakwater	Santa Monica Beach
1957	780,000	Santa Monica Breakwater	Santa Monica Beach
1969	389,800	Marina del Rey Bypassing	Dockweiler Beach
1973	16,098	Marina del Rey Bypassing	Dockweiler Beach
1975	10,000	Marina del Rey Bypassing	Dockweiler Beach
1980	266,000	Marina del Rey Bypassing	Dockweiler Beach
1981	217,435	Marina del Rey Bypassing	Dockweiler Beach
1987	35,315	Marina del Rey Bypassing	Dockweiler Beach
1992	21,500	Marina del Rey Bypassing	Dockweiler Beach
1994	57,000	Marina del Rey Bypassing	Dockweiler Beach
1996	238,000	Marina del Rey Bypassing	Dockweiler Beach
1998	125,825	Marina del Rey Bypassing	Dockweiler Beach
1999	820,089	Marina del Rey Bypassing	Dockweiler Beach
Total Bypassing	3,997,062	Average annual bypassing for Marina del Rey	62,500

Table 6.4: Sand bypassing for the Santa Monica littoral cell. Sources: USACE Los Angeles District (contact: Mo Chang 2001 and 2005); (Griggs, 1987b); (Leidersdorf et al., 1994)

million yd^3 of sand were excavated from the sand dunes between the Hyperion facility and the City of El Segundo and placed along 8,600 ft of Dockweiler beach to mitigate the erosion caused by the Ballona Creek jetties (Wiegel, 1994). The City of Los Angeles constructed two stone groins 4,600-ft and 8,600-ft long in 1956 to help stabilize and maintain the nourished sand on the beach (Pardee, 1960; Wiegel, 1994).

C. Marina del Rey to Redondo/King Harbor: The stretch of shoreline from Marina del Rey to Redondo/King Harbor consists of wide, sandy beaches, stabilized by rock groins, backed by parking lots and park facilities (Figure 6.3). A small stretch of shoreline near El Segundo Beach (Figure 6.1) is backed by bluffs. Erosion of these bluffs under natural conditions was found to contribute ~500 yd^3/yr of sand, but these bluffs are now protected leading to a reduction of ~56% (or 1,300 yd^3/yr) due to bluff armoring. As previously discussed, Dockweiler State Beach (Figure 6.3) has been nourished over the years with the sand bypassed from Marina del Rey (Table 6.4).

Just downcoast of Dockweiler State beach, El Segundo Beach was nourished with 620,000 cubic yards of sand in 1984, concurrent with construction of El Segundo Marine Terminal Groin, a 915-foot-long rubble-mound structure. Five-hundred and seventy thousand cubic yards of sand were placed updrift of the groin and 50,000 cubic yards of sand were placed downdrift of the groin to prevent future erosion (Leidersdorf et al., 1994). Most of the sand for this nourishment project came from an offshore borrow area in 25 to 45 feet of water depth (Leidersdorf et al., 1994; Moore, 1983). In 1947, 100,000 yds^3 of sand, from an onshore source, were placed on Redondo Beach south of the north breakwater for King Harbor (Table 6.3).

King Harbor (Figure 6.9), completed in 1959 and named after a local congressman, provides anchorage for boaters, and its waterfront restaurants and shops are a destination for visitors to Redondo Beach. The harbor is located at the head of Redondo Submarine Canyon, which was discovered to come within 200 feet of the shoreline in 1890. Initially, a pier was built near the canyon to allow ocean-going ships a place to dock, however there was no protection for these ships against large storm waves. Construction of a 1,485-foot long, shore-parallel breakwater was approved in 1938 and built in 1939 at the cost of $50,000 to provide protection to the ships docked at the pier. This breakwater resulted in severe erosion of the beaches downcoast, however. In 1958, the breakwater was reconstructed and extended 2,800 feet to the south. King Harbor was then constructed by adding a dogleg to the existing breakwater and adding a second breakwater on the south side of the harbor to form the entrance channel between the two structures. Because of its proximity to the head of Redondo Submarine Canyon, this harbor does not require maintenance dredging. Substantial downdrift erosion has resulted from the construction of King Harbor because of sand trapping along the northern margin of the breakwater and the deflection of sand into Redondo Canyon.

D. Redondo Canyon to Malaga Cove: The presence of King Harbor and the mouth of Redondo Submarine Canyon effectively form a 2.8-mile-long sub-cell or beach compartment between the southern breakwater of the harbor and Malaga Cove. This historically narrow beach is backed by 30 to 140-foot-high bluffs that were found to contribute an average of 3,700 yd3/yr of beach-sized sand (coarser than 3Ø) annually. In 1947 and again in 1962, Los Angeles County placed 220,000 cubic yards of sand (source unknown) on the beach (USA/CESPL, 1966a; 1970; Wiegel, 1994) (Table 6.3).

Topaz Street groin, built in 1970, bisects the sub-cell even further. Along the short stretch of shoreline from Redondo canyon to the Topaz Street groin, littoral drift travels north and sand is eventually lost into Redondo Canyon.

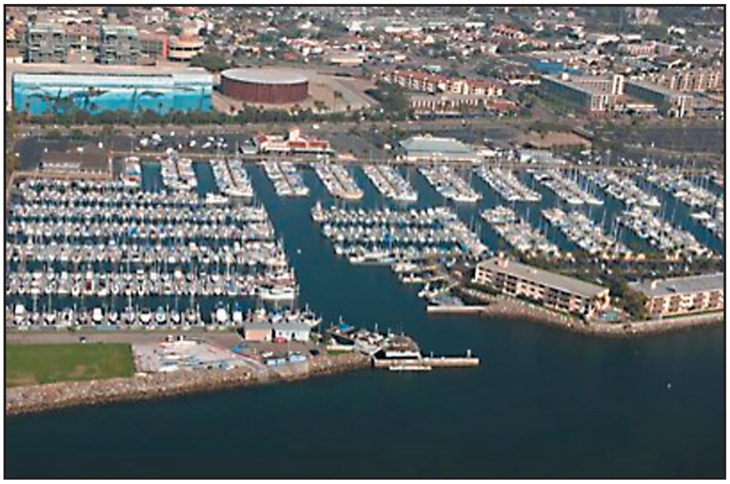

Fig 6.9: Entrance to King Harbor. Copyright © 2002 Kenneth & Gabrielle Adelman

From the groin south to Malaga Cove, the beaches are relatively stable. In 1968-1969 these beaches were nourished with 1.4 million yds^3 of sand obtained from ~1,700 feet offshore in water depths of 30-60 feet (Table 6.3)(Anonymous, 1969; Fisher, 1969; USA/CESPL, 1970; Wiegel, 1994). The result of this nourishment activity was to widen the beach by ~300 ft by 1969 (Leidersdorf et al., 1994). The 590-foot-long Topaz Street groin has been successful at stabilizing the beach (Herron, 1986). Much of the original sand from the nourishment project still exists along the stretch of coast from the groin to Malaga Cove (Corporation, 1992; Leidersdorf et al., 1994; Wiegel, 1994).

E. Malaga Cove to Palos Verdes Peninsula: Palos Verdes Peninsula is a large headland, which separates the Santa Monica and San Pedro littoral cells. Extensive seacliffs characterize this stretch of coastline, and are a result of almost 1,500 feet of tectonic uplift. Palos Verdes Peninsula is separated from the Los Angeles Basin by the Palos Verdes Fault. A few, small, pocket beaches formed by cobbles rather than sand exist around this peninsula. Erosion of Palos Verdes Peninsula was found to contribute ~133,000 yd^3/yr of sand-sized material annually on average (much of this material is cobble-size). Landslides are common along the peninsula and occur along 53% of the shoreline between Abalone Cove and Point Fermin (Griggs et al., 2005). On the south side of the peninsula, at Portuguese Bend, is the site of the largest, most destructive landslide in this area. Roughly $65 million dollars of property damage occurred with the total destruction of 150 homes on 300 acres during this slide.

CONCLUSIONS

Dams and seacliff armoring have reduced the total amount of sand entering the Santa Monica littoral cell by approximately 31,000 yd^3/yr (Table 6.2). Beach nourishment, however has provided over 33 million cubic yards of sand (~538,000 yd^3/yr) since 1926, effectively widening the beaches in the central and southern portions of Santa Monica Bay by ~150 to 500 feet. Leidersdorf et al. (1994) note that 95% of the sand from beach nourishment projects was placed on the beaches prior to 1970. Since then, the number of nourishment opportunities and projects has significantly decreased. This may be a reason for the perception that the beaches in this cell are currently narrowing. Currently, Professor Tony Orme and two graduate students in the Geography Department at the University of California, Los Angeles, are completing a study of long-term beach width change in southern California that should shed light on the changes that have taken place over the past 50 or 60 years.

The sand budget for the Santa Monica littoral cell is illustrated in Figure 6.10 as a simple box model with sand entering each sub-cell through rivers, seacliff or bluff erosion, and beach nourishment. Sand leaves the cell when it is lost into submarine canyons. Due to the extensive use of groins, this cell is highly compartmentalized resulting in a large storage component; little sand flows from one sub-cell to the other, with the exception of the by-passing operation at Marina del Rey where sand is moved from sub-cell B and placed into sub-cell C. Because of the large storage of sand behind groins and other retention structures, the volume of sand currently entering Redondo Submarine Canyon is unknown.

Rivers historically provided 40% of the littoral sand to this cell (~100,000 yd^3/yr) with bluff erosion providing the remaining 60%, or 150,000 yd^3/yr (Table 6.2). Thus, the total input of sand into the Santa Monica cell was naturally almost 250,000 yd^3/yr. Damming of the rivers reduced the sand input to 70,000 yd^3/yr, which is a decrease of 29,000 yd^3/yr or 30% of the natural yield (Table 6.2). Bluff armoring reduced the supply of sand from seacliff or bluff erosion by 1% or ~2,000 yd^3/yr bringing the actual, or present-day, contribution of sand from cliff erosion to 148,000 yd^3/yr (Table 6.2).

By far, the largest contributor of sand to this littoral cell, constituting 66% of the actual total sand budget, is beach nourishment. Since 1926, over 29 million cubic yards of sand (or about 432,000 yd^3/yr if averaged from 1926-1988; 428,000 yd^3/yr if averaged over the last 78 years from 1926 to 2004) has been placed on the beaches in this cell (Table 6.5). This is nearly twice as much sand as currently enters the cell from rivers (~70,000 yd^3/yr) and bluff erosion (~148,000 yd^3/yr) combined, a total of 218,000 yd^3/yr. Beach nourishment, in conjunction with the emplacement of structures to retain the fill material, has allowed wide, sandy beaches to be built and to remain relatively stable in the central and southern reaches of this cell.

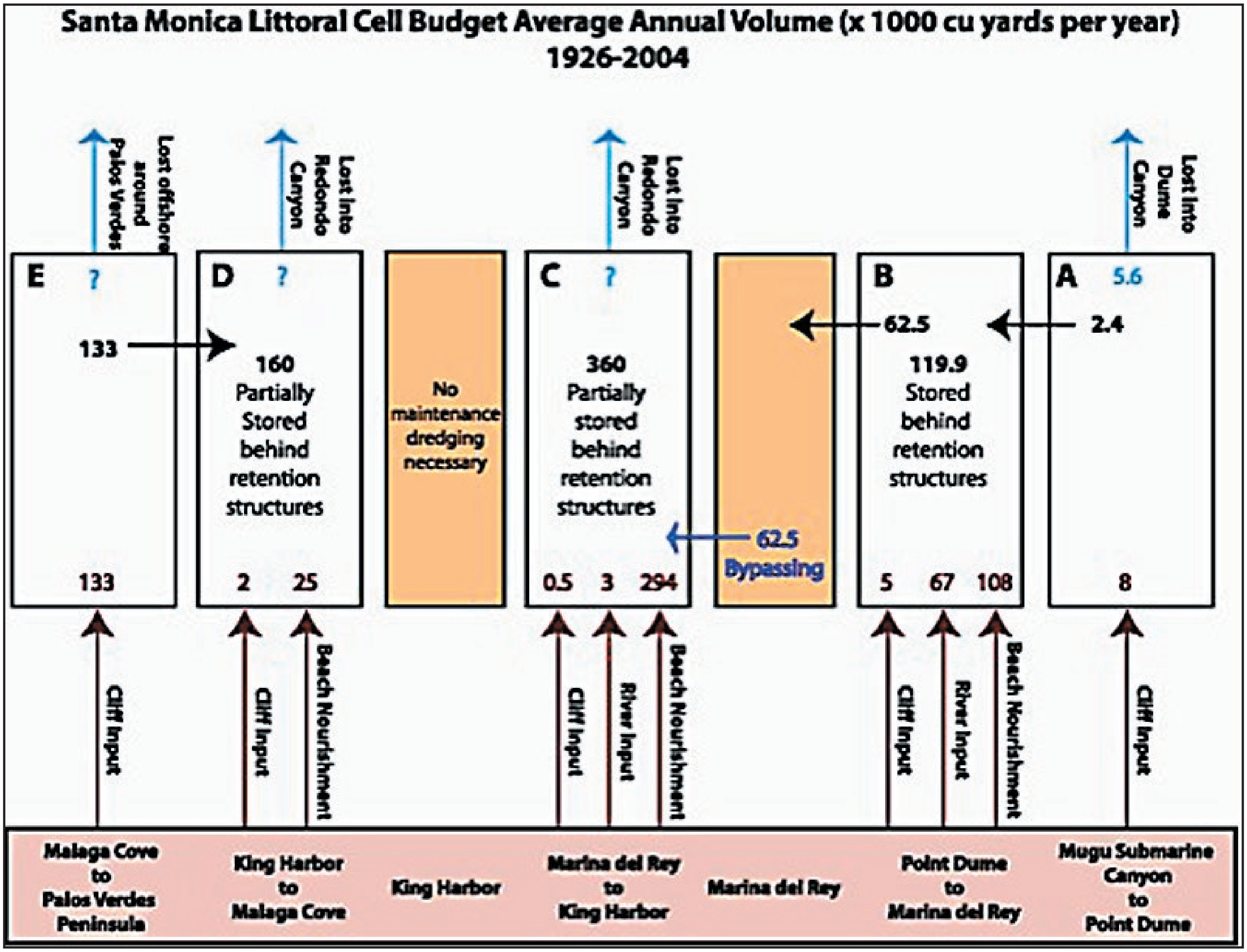

Fig 6.10: Santa Monica littoral cell budget- Box Model. Averages are representative from 1926 to 2004

With an increase in El Niño storm events (which increased wave energy causing increased erosion), and a decreasing trend in the nourishment projects in this cell, it is expected that the beaches will eventually return to their natural, narrow, sand-starved state. As for now, million of people enjoy these artificial, wide, sandy beaches every year.

	Sub-cell	Quantity (yd^3)	Annual Quantity over the last 78 years (yd^3/yr)
Total 1926-2004	ALL	33,360,000	428,000
Total 1926-2004	B	8,450,000	108,000
Total 1926-2004	C	22,970,000	294,000
Total 1926-2004	D	1,940,000	25,000

Table 6.5: Total Volume of sand added through artificial nourishment to each sub-cell in the Santa Monica littoral cell. Sub-cells: B= Point Dume to Marina del Rey; C= Marina del Rey to Redondo/King Harbor; D= Redondo/King Harbor to Malaga Cove.

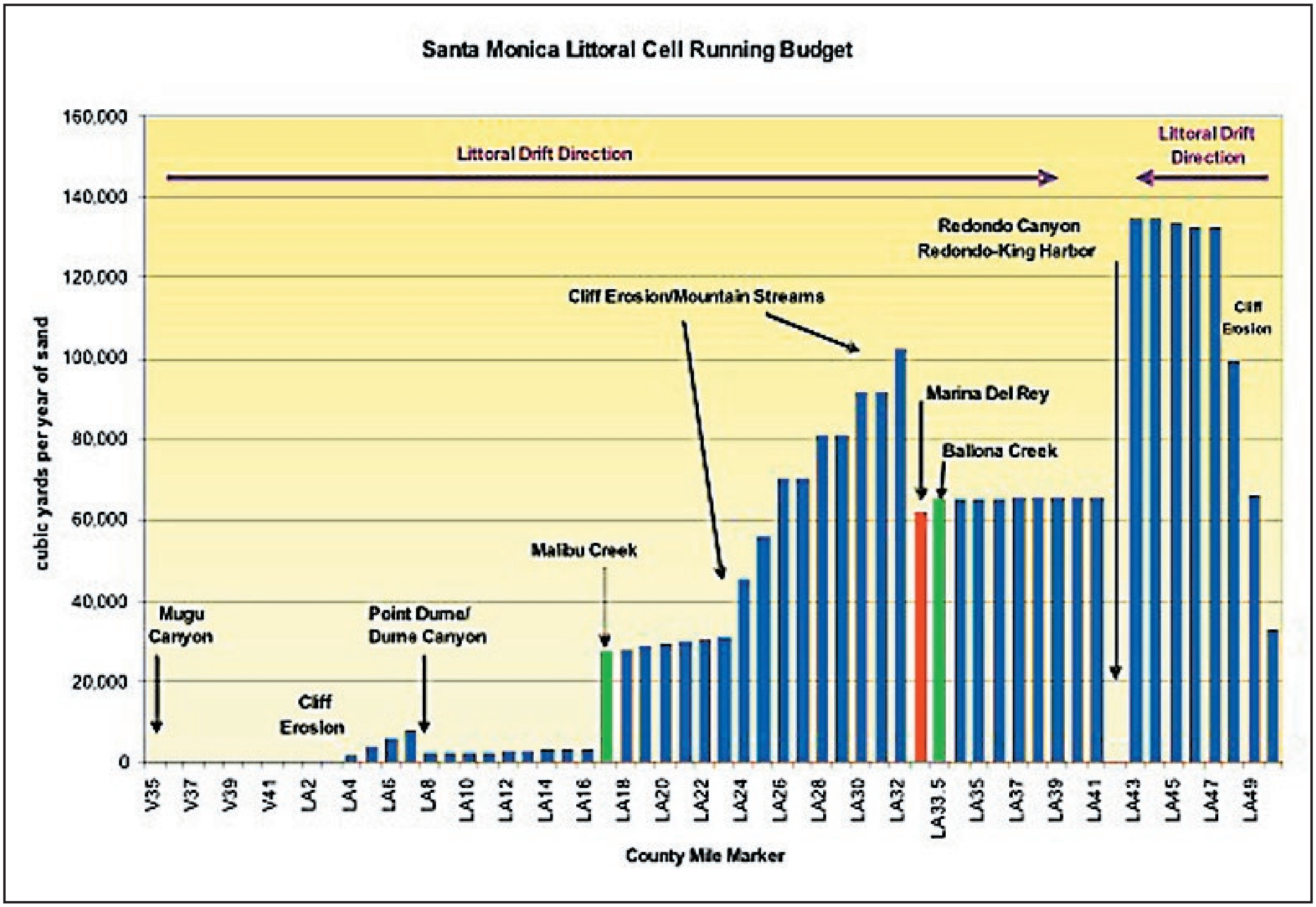

Fig 6.11 portrays the Santa Monica littoral cell budget as a mile-by-mile running total of sand moving as littoral drift through the cell. This illustration shows what the alongshore running budget would look like in its natural state with no groins inhibiting the flow of littoral drift and no additional sand added as beach nourishment. Marina del Rey is used as a constraint and check-point for the budget. Redondo Canyon is the major sink for the cell in its "natural" state.

Chapter 7

San Pedro Littoral Cell Sand Budget

The San Pedro littoral cell extends ~31 miles southeast from Point Fermin, just south of the Palos Verdes Peninsula, and terminates at Corona del Mar, located south of Newport Bay (Figures 7.1 and 7.2). The majority of the shoreline consists of low-lying coastal plains and barrier spits with a small reach of coastal bluffs at Huntington Cliffs. Because of the low-lying nature of this shoreline, coastal hazards associated with beach erosion and storm-induced flooding are extensive.

The shoreline of the San Pedro littoral cell has experienced significant changes as a result of the extensive use of shoreline engineering structures and coastal development. The largest event impacting this stretch of shoreline was the construction of the Los Angeles/Long Beach Harbor complex initiated in 1889.

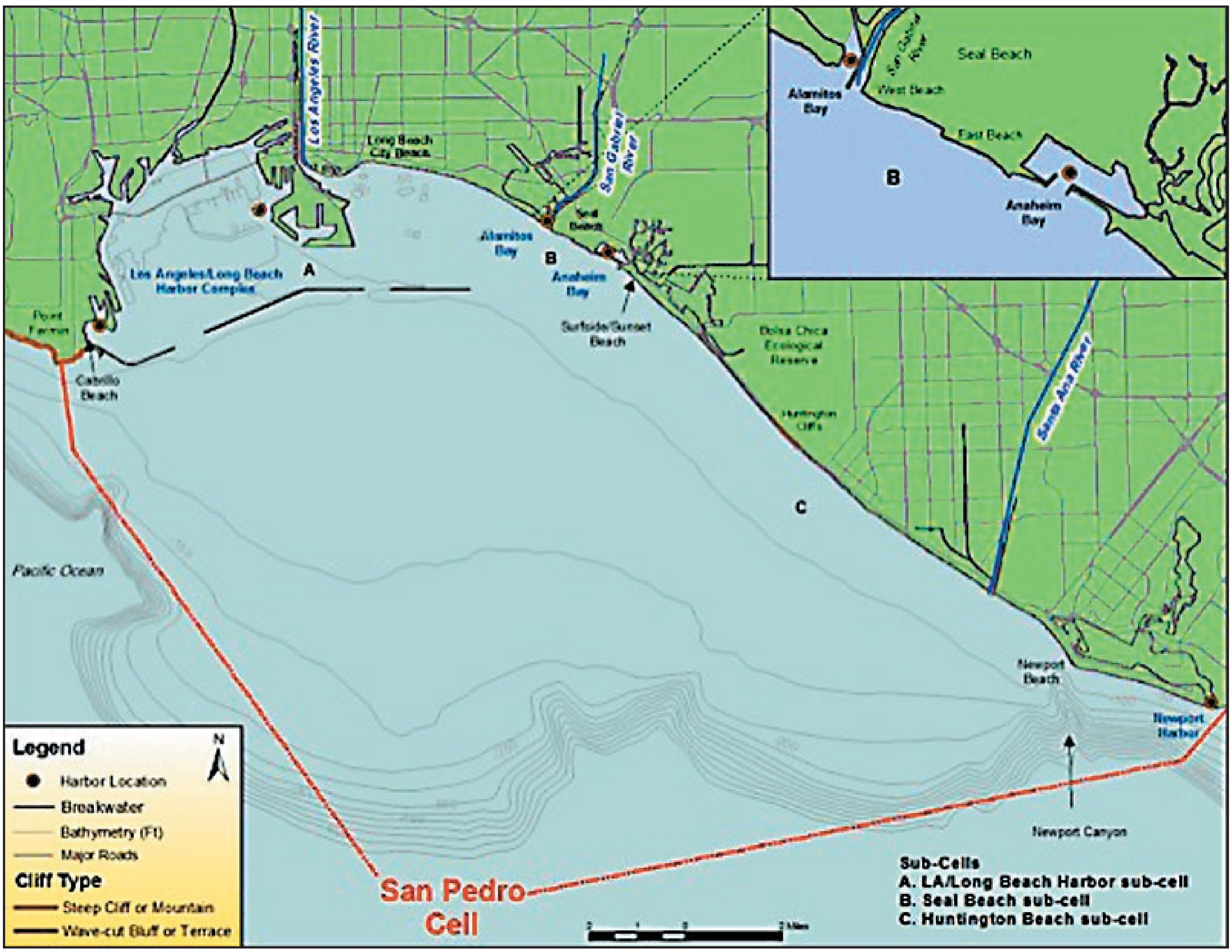

Fig 7.1: Map of the San Pedro littoral cell. Inset shows a close-up of the Seal Beach Sub-cell

The construction of the San Pedro, Middle, and Long Beach breakwaters essentially isolated the 9-mile-long stretch of coast, from Point Fermin to Seal Beach, from the rest of the littoral cell. The coast was further compartmentalized with the construction of jetties at the mouth of the San Gabriel River and the inlet stabilization projects at Anaheim and Newport bays. The construction of dams and debris basins on some of the largest rivers in the cell, which contribute the majority of naturally derived sand, significantly changed the condition of the beaches in the San Pedro littoral cell.

The shoreline of the San Pedro littoral cell has been compartmentalized into three sub-cells due to the extensive use of shore-normal coastal engineering structures, which disrupt the flow of littoral drift and essentially create self-contained sub-cells within the more broadly defined San Pedro littoral cell. The sub-cells are defined as follows: A. Los Angeles/Long Beach Harbor sub-cell, extending from Point Fermin to the west jetty of Alamitos Bay; B. Seal Beach sub-cell, extending from the east jetty of the San Gabriel River to the west jetty of Anaheim Bay; and C. Huntington Beach sub-cell, extending from the east jetty of Anaheim Bay to Corona del Mar (see Figure 7.1).

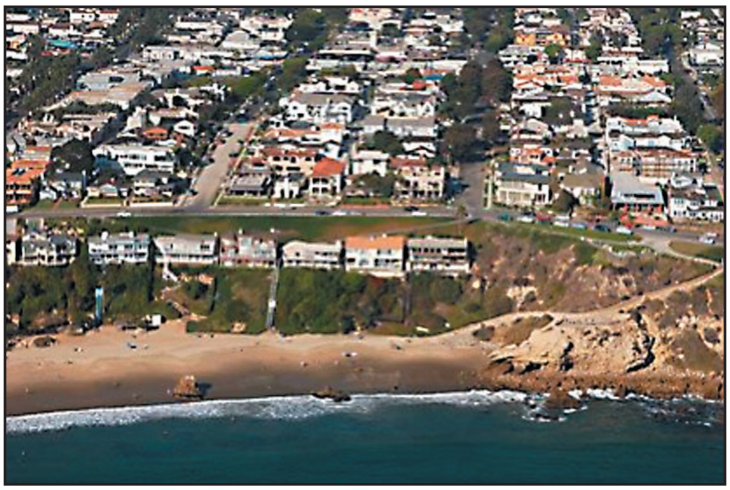

Fig 7.2: Inspiration Point, Corona del Mar, showing beginning of cliffs and the end of the San Pedro littoral cell, 2002.

SAND SOURCES

Rivers: The three largest rivers draining into southern California, the Los Angeles, San Gabriel and Santa Ana rivers, all provide sand to the San Pedro cell; in addition, a small amount of sand is derived from San Diego Creek. Although the sand loads of these rivers, with the exception of San Diego Creek, have been greatly reduced by dams, debris basins, and/or channelization, they are still the main natural source of sand to this cell.

The Los Angeles River is one of the most heavily altered fluvial systems in the United States (Griggs et al., 2005). Dams, debris basins, and channelization have reduced the transport of sand from this river to almost nothing. The San Gabriel River, located four miles to the east of Seal Beach, still transports sand to the coast during floods; however, like the Los Angeles River, the volume of sand discharged has been reduced due to the effects of dams and debris basins. An average of over 810,000 cubic yards per year of sand (sediment coarser than 0.0625 mm) was originally delivered to the beaches by the Los Angeles, San Gabriel and Santa Ana rivers and San Diego Creek (Willis and Griggs, 2003; Willis et al., 2002). Damming of these rivers has reduced the total sand load by 66% to an average of 278,000 cubic yards annually. Rivers naturally provided 99.8% of the sand to the overall littoral cell sand budget, and today provide only 40.9% of the sand entering this cell (Table 7.1).

Specifically, the sand load of the Los Angeles River has been reduced by about 67%, from an average of ~233,000 yd^3/yr to ~77,000 yd^3/yr as a result of damming. Dams also reduced the sand yield of the San Gabriel River by approximately 67%, from an annual average of ~182,000 yd^3/yr to ~59,000 yd^3/yr. The Santa Ana River has also been reduced by 67%, from an annual average of ~379,000 yd^3/yr to ~125,000 yd^3/yr. San Diego Creek is not dammed and thus the average annual sand yield of ~16,000 yd^3/yr has not diminished significantly.

San Pedro Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	810,100 (99.8%)	278,000 (40.9%)	532,100 (65.7%)
Bluff Erosion	2,000 (0.2%)	2,000 (0.3%)	0 (0%)
Beach Nourishment		400,000 (58.8%)	+400,000
Total Littoral Input	812,100 (100%)	680,000 (100%)	132,100 (16%)

Table 7.1: Overall sand contributions and reductions to the San Pedro littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Because the Los Angeles River discharges sand behind the breakwaters of the Los Angeles/Long Beach Harbor complex, waves do not have the opportunity to carry this sand down coast as littoral drift. The sand essentially stays within the harbor until it becomes a navigational hazard and must be dredged. Dredged material is typically placed on Cabrillo Beach just upcoast, or Long Beach, immediately downcoast.

Debris Basins: Debris basins are small catchments, typically with capacities between 1,000 and 5,000 cubic yards, designed to allow the passage of water and fine sediments while trapping or retaining coarse sediment. These basins are created by building small dams across ephemeral stream channels. The purpose of these barriers is to reduce the danger of debris flows by trapping the main source of transported material. To remain functional, the accumulated sediment must be removed routinely from the debris basins (Willis et al., 2002). The Los Angeles Department of Public Works has a protocol for the management and clean-out of debris basins based on fire history and the loss of storage volume.

In California, the majority of debris basins are built around the perimeter of the Los Angeles basin, in the San Bernadino, San Gabriel, Santa Monica, and Santa Susana Mountain watersheds. As of 1978 almost 14 million cubic yards of material had been removed from over 100 debris basins in Ventura, Los Angeles, San Bernadino, Riverside, Orange and San Diego Counties (Willis et al., 2002). For most of these projects, grain-size information on the removed sediment is minimal; thus, the percentage of sand-sized sediment removed is unknown (Kolker, 1982; Willis et al., 2002). Taylor (1981) states that it is reasonable to assume ~50% of the sediments are within the sand-size range. Using this value, ~7 million cubic yards of sand-sized sediment has been removed from the debris basins listed above as of 1978. It is assumed that sediment removed from debris basins represents a permanent sink or loss of sand to a littoral cell sediment budget, as this material is transported to on-land disposal or depositional sites.

As of 2000, Willis et al. (2002) estimated that 163 basins have trapped more than 18 million cubic yards of debris over the cumulative periods of operation, 17,600,000 cubic yards of debris, have been removed to maintain the functionality of the debris basins. Using Taylor's (1981) 50% sand content estimate, Willis et al. estimated that ~9 million cubic yards of sand have been trapped and effectively removed from the littoral budgets in southern California.

While the overall effect of debris basins appears to be the removal of a large volume of sand from the littoral budgets in southern California, the effect of individual structures is minimal. Average sedimentation rates exceeding 1,000 cubic yards annually occur in 82 out of the 182 basins. Only 13 of the 162 basins have average sedimentation rates over 10,000 cubic yards per year (Willis et al., 2002). Applying Taylor's (1981) assumption of a 50% sand content in the trapped material, only three debris basins (Little Dalton, Big Dalton, and Santa Anita) trap an average of more than 10,000 yd^3/yr of sand (Willis et al., 2002).

The Los Angeles River watershed has 85 debris basins with a combined capacity of almost 6 million cubic yards, which capture an average of ~3,200 cubic yards of sand annually (~1,600 yd^3/yr of sand-sized material). The San Gabriel River watershed has 21 debris basins with a combined capacity of almost 2 million cubic yards that capture an average of 3,400 yd^3/yr of sand annually (~1,700 yd^3/yr of sand-sized material) (Willis et al., 2002). Overall, debris basins have a minimal effect on the overall sand budget for littoral cells in southern California.

Channelized Streams: A stream is considered to be channelized when "its bed has been straightened, smoothed, or deepened to permit the faster flow of water" (Bates and Jackson, 1984; Willis et al., 2002). Flood control and bank stabilization are the two main reasons to channelize a stream in an urban watershed. According to Mount (1995), urbanization has the following effects on flood hydrographs: 1. the lag-time between peak rainfall intensity and peak run-off decreases; 2. the magnitude of flood peaks increase; and 3. there is an increase in the total run-off volume. Channelization of streams in urban areas attempts to prevent flooding by collecting run-off from impermeable surfaces efficiently.

Hard bottom channels create problems with sediment deposition when the channel can no longer transport the sediment load. The build-up of sediment must be excavated to prevent back-up and flooding. In Los Angeles County, the Department of Water and Power (LADWP) must maintain 460 miles of channels. In 1998 and 1999 LADWP excavated 43,809 tons of sediment from these channels (Willis et al., 2002).

Channelized streams also prevent the lateral and downward incising or erosion of the stream bed that can naturally supply beach-size sediment to the shore, thus reducing the sand budget. Willis et al. (2002) found that due to a lack of data collection and book-keeping concerning channelization and sediment removal from stream channels, it is not possible to assess the significance of this sediment removal to the overall sand budgets in the southern California littoral cells.

Cliff or Bluff Erosion: The San Pedro littoral cell only has one small section of low, Pleistocene-aged coastal bluffs at Huntington Cliffs. These bluffs extend alongshore for ~3,800 feet and have an average height of 100 feet. The littoral cut-off-diameter, or the coarsest sediment grain size that will remain on the beaches in this area, was determined to be 3.25ø (0.105 mm). It was determined that contributions from bluff erosion represent 0.3% of the total sand budget for the San Pedro littoral cell by contributing an average of only ~2,000 yd^3/yr of sand annually (Table 7.1).

Beach Nourishment: Harbor and river channel projects over the last 60 years in the San Pedro Cell have contributed 25 million yds^3 of sand used as nourishment on 15 miles of public beaches in the San Pedro littoral cell (Coastal Frontiers Corporation, 2000; Herron, 1980; Wiegel, 1994). Federal, state and local governments developed and fund an ongoing beach nourishment project, which uses Surfside/Sunset Beach as a feeder location and contributes an average of nearly 400,000 yds^3 of sand per year (Flick, 1993). Beach nourishment contributes 58.8% of the sand to the budget in the San Pedro littoral cell (Table 7.1).

SAND SINKS

Submarine Canyons: Newport Submarine Canyon is located just upcoast of Newport bay (Figure 7.1). In the past, the canyon served as the main sink for littoral drift traveling through this cell. However, the construction of jetties to stabilize the entrance into Newport Harbor, in addition to a reduction in longshore transport due to the construction of the San Pedro, Middle, and Long Beach breakwaters, and the groin field at West Newport Beach, effectively trapped sand before it was lost into the canyon (Coastal Frontiers Corporation, 2000). During the past few decades, researchers have found that little sand has been lost into Newport Canyon (Everts, 1991; Everts and Eldon, 2005; Felix and Gorsline, 1971; Habel, 1978; Wiegel, 1994). Everts and Eldon (2005) conclude that an average of approximately 1,000 yd^3 is lost into the canyon annually.

Subsidence: As a result of the withdrawal of oil and gas from the large Wilmington Oil Field and the Huntington Oil Field dating back to the 1930's, much of the coastline has subsided contributing to beach retreat (Coastal Frontiers Corporation, 2000; Flick, 1993; Griggs et al., 2005). The withdrawal of oil creates a shallow seafloor depression offshore, which ultimately fills with sediment from the nearshore zone, essentially removing this sand from the littoral cell budget. Between 1926 and 1968, Long Beach and Terminal Island subsided substantially, a maximum of 29 feet, (Allen and Mayuga, 1970; Wiegel, 1994), the mouth of the Los Angeles River subsided 9 feet (Allen and Mayuga, 1970; Bush and Steinbrugge, 1961), and Alamitos Bay subsided 15-18 inches (USA/CESPL, 1966b). The subsidence in this littoral cell is equivalent to the loss of over 6.5 million cubic yards of sand (Flick, 1993). Near Huntington Beach, the volume of the subsidence depression is over 20 million cubic yards (Coastal Frontiers Corporation, 1996; 2000). This represents a potentially significant loss of sand to the San Pedro littoral cell. Although about 15 million barrels of oil continue to be extracted from this oil reservoir, the initiation of a subsurface seawater injection program allowed for rebound and a significant reduction of the subsidence, thereby preventing further losses of sediment from the nearshore zone.

Offshore Losses: Sand may be lost offshore and effectively removed from the littoral cell budget by large storm events. This loss is not well understood in the San Pedro littoral cell, and has not been quantified by previous researchers. Estimates of offshore losses of sand are assumed to be in balance with sand entering the cell from offshore such that there is no net gain or loss. Because of the complex nature of the on- and offshore exchange of sand, estimates were not made in the present study to quantify this component of the sand budget.

Aeolian Deposits Inland: Inland transport of wind-blown sand and the formation and growth of dunes can, in some littoral cells, serve as a significant sink for sand. The potential for sand loss to dunes exists at Seal Beach, Newport Beach, and along Huntington Beach. However, these losses are assumed to be minor and were not quantified for this report.

LONGSHORE SAND TRANSPORT AND LITTORAL CUT-OFF DIAMETER

At different times of the year, waves transport sand in both directions along the shoreline of the San Pedro littoral cell. The net longshore transport of sand, however, is directed to the southeast from Surfside-Sunset Beach, just south of Anaheim Bay, to Newport Bay (Coastal Frontiers Corporation, 2000). Beach sand in the swash zone of this cell was sampled and sieved in this study to determine the average littoral cut-off diameter, which was determined to be 3.25Ø (0.105 mm).

Shore-normal engineering structures such as jetties and groins impound sand to varying degrees and prevent the uninterrupted transport of sand along the entire length of this cell. These structures compartmentalize the shoreline, and, as a result, the San Pedro cell is now divided into sub-cells. There is little to no natural transport of sand between these sub-cells; however, occasionally, sand may be moved from one sub-cell to another for nourishment purposes. In addition, shore-normal structures cause the storage of sand within these sub-cells creating wider beaches than would exist naturally.

SUMMARY OF THE SAND BUDGET FOR THE SAN PEDRO LITTORAL CELL

Los Angeles/Long Beach Harbor Sub-cell: Point Fermin to Alamitos Bay: The Los Angeles/Long Beach Harbor complex sub-cell extends 9 miles from Point Fermin to the west jetty of Alamitos Bay. This shoreline is protected from waves by three breakwaters creating the Los Angeles/Long Beach Harbor complex. Without the wave energy to drive the alongshore movement of sand, littoral drift is nonexistent. Sediment delivered by the Los Angeles River only serves to clog the harbor, and eventually must be dredged from the area to prevent navigational hazards.

Los Angeles/Long Beach Harbor complex was created by the construction of more than eight miles of stone breakwaters within San Pedro Bay. The breakwaters were built in three segments: San Pedro Breakwater, the western most structure, was built in 1912, and extends 11,152 feet in an easterly direction from the shore near Point Fermin; Middle Breakwater is an 18,500-foot-long detached breakwater constructed in the mid 1930's; and the 13,350-foot-long Long Beach Breakwater, is a detached structure built in 1948-49 (Wiegel, 1994). More than 18 square miles of harbor are protected behind these breakwaters (Figure 7.3; USA/CESPL and CA/DNOD, 1978; Wiegel, 1994). The space between the San Pedro and Middle breakwaters serves as the entrance channel to Los Angeles Harbor, and the channel between the Middle and Long Beach breakwaters serves as the entrance to Long Beach Harbor. Because of the location of these harbors at the northwestern end of the littoral cell, where little to no littoral drift is making its way around Point Fermin, these channels require only minor maintenance dredging on the order of once ever 10 years (Wiegel, 1994). The entrance channel to Los Angeles Harbor has been dredged three times since 1980, with an average dredged volume of about 22,000 yd^3/yr (Table 7.2). Long Beach Harbor's entrance channel, between Middle and Long Beach breakwaters, has been dredged only five times since 1970 with an average volume of ~32,000 yd^3/yr removed from the channel (Table 7.2). By reducing the wave energy reaching the shoreline in the lee of the breakwaters and ultimately eliminating longshore drift, the original beaches between Long Beach and Seal Beach have been significantly impacted by the harbor construction (Wiegel, 1994).

Within Los Angeles and Long Beach harbors, channels are dredged to a depth of -45 feet MLLW by the Corps of Engineers. Dredging to greater depths is the responsibility of the Port of Los Angeles. Dredge material is either disposed of in the LA-2 disposal site, at an upland disposal area, or used as beach nourishment. LA-2 was designated by the Environmental Protection Agency (EPA) in 1991 as an ocean disposal site for dredge material from the Los Angeles/Long Beach harbor complex located near the edge of the continental shelf, 7.7 miles south of the San Pedro Breakwater. The offshore site area is approximately 2.4 square miles with water depths ranging from 387 to 1,050 feet. Upland disposal of clean material occurs at a location adjacent to the East Basin at the northeastern edge of the Los Angeles Harbor, and is used by the Port of Los Angeles and the Corps of Engineers.

When emergency dredging is required, material is often disposed of in the 600'-by-600' borrow pit located at the mouth of the Los Angeles River. The pit has a maximum depth of -75 feet MLLW, and has a capacity of ~1.7 million cubic yards. The construction of San Pedro Breakwater created the largest artificial beach in southern California, known as Cabrillo Beach (Flick, 1993). The beach is 2,400-feet-long and extends from the ocean side of San Pedro Breakwater northwest where it adjoins the land on the east side of Point Fermin (Figure 7.3). The southern end of the beach is held in place by a 745-foot-long rubblemound groin, built in December of 1962 (Wiegel, 1994). Before the groin was built to stabilize the beach, previous attempts at creating a beach ultimately failed because the sand was lost offshore. In 1927 and again in 1948, 500,000 yd^3 and 2.9 million yd^3 of sand, respectively, dredged from Los Angeles Harbor, were placed on the beach. Most of this sand was ultimately lost offshore (USA/CESPL, 1989; Wiegel, 1994). After the construction of the groin in 1963, 1.2 million yd^3 of sand dredged from the west basin of Los Angeles Harbor was placed onto Cabrillo Beach and proved successful (Dunham, 1965; Herron, 1986; Price, 1966; USA/CESPL, 1989; Wiegel, 1994). However, during the El Niño winters of 1982/83 and 1997/98 Cabrillo Beach experienced significant erosion (USA/CESPL, 1989; Wiegel, 1994). In 1991, Cabrillo Beach was again nourished with 220,000 yd^3 of sand from the Hyperion facility (Wiegel, 1994).

Fig 7.3: Cabrillo Beach, the San Pedro Breakwater, and the Los Angeles Harbor. Copyright © 2002 Kenneth & Gabrielle Adelman

Long Beach City Beach is another wide, sandy beach, which receives large amounts of beach nourishment. Between 1943 and 1946, 6 million yd^3 of sand dredged from the Los Angeles River delta for flood control purposes was placed on this beach. This nourishment project remained stable and was considered successful because the beach is located in the lee of the breakwater and is protected from wave induced erosion (Wiegel, 1994).

Prior to 1868, the Los Angeles River joined the San Gabriel River upstream from San Pedro Bay. In 1868, extensive flooding caused the San Gabriel to split creating a new channel into Alamitos Bay six miles south of the previous outlet (Kenyon, 1951; Wiegel, 1994). The lower reach of the San Gabriel River became known as the Los Angeles River, and the channel, which spit off into Alamitos Bay, became known as the "new" San Gabriel River. The Los Angeles River currently discharges between Los Angeles and Long Beach harbors directly behind the Queen Mary cruise ship (Figure 7.4).

In 1921, the Los Angeles River was channelized; however, originally no jetties were constructed at its outlet to divert sediment offshore into deeper water. Thus, a delta formed at the mouth of the river; this delta is periodically dredged to provide nourishment to Cabrillo and Long Beach beaches.

Year	LA Harbor	Long Beach Harbor	Alamitos Bay	Anaheim Bay	Newport Harbor
1971				2,260,000	
1972				0	
1973				0	
1974				0	
1975				0	
1976				0	
1977				0	
1978				0	
1979		355,000		0	
1980	356,000	0		0	
1981	0	0		0	81,000*
1982	0	0		0	0
1983	0	0		1,060,000*	0
1984	0	0		1,245,000*	0
1985	0	0		0	0
1986	0	0		0	0
1987	0	0		0	0
1988	0	0		0	0
1989	0	0		0	0
1990	0	0		0	0
1991	0	122,238		0	0
1992	0	0		0	0
1993	0	0		0	0
1994	0	0		0	0
1995	47,022	0		0	0
1996	0	0		0	0
1997		62,426		0	0
1998	122,930	0		0	268,403
1999	0	165,233		331,704	0
2000	0	0		0	0
2001	0	135,171		0	0
2002	0	0		0	0
2003	0	0		0	26,991
2004	0	0		0	0
Average	21,915	32,310	0	144,021	15,683

Table 7.2: Dredging Histories for Harbors in the San Pedro Littoral Cell. Source: Mo Chang (2001; 2005), USACE- LA District, Personal Communication and *Griggs (1987b)

The Los Angeles River under natural conditions transported an average of 233,000 yd^3 of sediment annually. This sediment yield has been reduced about 67% by the construction of dams, debris basins, and channelization to an average annual volume of 77,000 yd^3. As previously mentioned, this sand does not travel as littoral drift because of the wave protection offered by the Los Angeles/Long Beach Harbor complex breakwaters. This sub-cells ends at Alamitos Bay, which will be discussed in the following section.

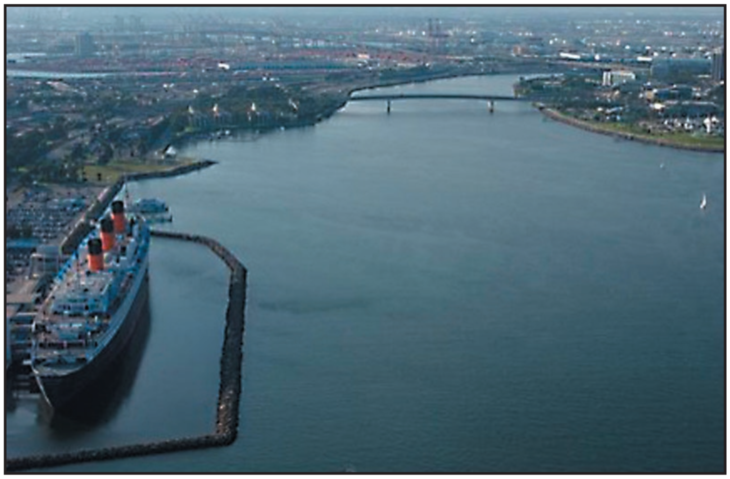

Fig 7.4: The Los Angeles River currently discharges directly behind the Queen Mary cruise ship in between the Los Angeles and Long Beach harbors. 2004. Copyright © 2002 Kenneth & Gabrielle Adelman

SEAL BEACH SUB-CELL: ALAMITOS BAY TO ANAHEIM BAY

Seal Beach sub-cell is a small self-contained stretch of shoreline comprising ~5,300 feet of beach between the San Gabriel River east jetty and the Anaheim Bay west jetty (Figure 7.1). Seal Beach is separated into West Beach and East Beach by a concrete groin built just north of Seal Beach Pier (Figure 7.1 and 7.5). A net northwesterly littoral drift exists in this small stretch of coast which is a result of the sheltering effects of the Long Beach breakwater and wave reflection off the west jetty of Anaheim Bay (Coastal Frontiers Corporation, 2000). Erosion of East Beach, due to the net northwestward littoral drift, has been alleviated by a combination of beach nourishment from outside sources and back passing of material from West Beach (Coastal Frontiers Corporation, 2000; Flick, 1993; Wiegel, 1994)(Tables 7.3 and 7.4).

Wiegel (1994) notes that there has been some discrepancy in the volume of beach nourishment reportedly placed on Seal Beach in 1959 following construction of a sheet pile groin adjacent to the Seal Beach pier. Either 250,000 yd^3 of sand dredged from the mouth of the San Gabriel River or 200,000 yd^3 of sand dredged from Anaheim Bay's entrance channel was placed on this beach, in addition to an unknown quantity of sand brought in by the city reported by Dunhan (1965). Walker and Brodeur (1993) report that the city of Seal Beach compensates for the transport of sand over and around the seaward end of the groin by backpassing sand every two years from the west side of the groin to the beaches on the east side of the groin (Tables 7.3 and 7.4). An artificial sand berm has been built on Seal Beach every winter since the 1960's in an attempt to prevent flooding due to storm-wave overwash (Griggs et al., 2005). The berm has prevented a great deal of damage to back-beach development; however, it is occasionally overtopped during El Niño winters (Griggs et al., 2005).

Fig 7.5: Seal Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

As mentioned previously, the San Gabriel River migrated approximately 2,800 feet to the southeast between 1868 and 1931 eventually discharging into Alamitos Bay. A new outlet to the ocean was constructed for the San Gabriel River in 1933 with the installation of two straight, parallel jetties; the east and west jetties are 725-feet-long and 375-feet-long (extended in 1940 to 725-feet-long) respectively. The new channel, excavated in 1935, provided sand to the surrounding beaches.

Fig 7.6: Entrance to Alamitos Bay and the mouth of the San Gabriel River, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

Eventually, a new, separate entrance channel for Alamitos Bay was engineered by constructing an additional 800-foot-long jetty parallel to and west of the other two jetties (Figure

Date	Source	Raw Quantity (cy)	Adjustment Factor	Adjusted Quantity (cy)
1967	San Gabriel River	35,000	0.80	28,000
1969	West Beach	130,000	1.00	130,000
1972	West Beach	33,400	1.00	33,400
1974	West Beach	3,000	1.00	3,000
1975	West Beach	5,400	1.00	5,400
1976	West Beach	1,800	1.00	1,800
1983	Anaheim Bay	250,000	0.32	80,000
1988	Anaheim Bay	110,000	0.80	88,000
			Total Quantity	369,000 cy
			Annual Nourishment	12,000 cy/yr

Table 7.3: Beach Nourishment History at East Beach (1963-1994). Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment which will not remain on the beaches unless a more rigorous grain size analysis was done to determine the percentage of beach-quality sediment. Source: Coastal Frontiers Corporation, 2000

Date	Source	Raw Quantity (cy)	Adjustment Factor	Adjusted Quantity (cy)
1967	Nourishment from San Gabriel River	35,000	0.80	28,000
1969	Back passed to East Beach	(-130,000)	1.00	(-130,000)
1972	Back passed to East Beach	(-33,400)	1.00	(-33,400)
1974	Back passed to East Beach	(-3,000)	1.00	(-3,000)
1975	Back passed to East Beach	(-5,400)	1.00	(-5,400)
1976	Back passed to East Beach	(-1,800)	1.00	(-1,800)
			Total Quantity	(-145,000)
			Annual Net Removal Rate	(-5,000) cy/yr

Table 7.4: Beach Nourishment and Back passing History at West Beach (1963-1994). Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment which will not remain on the beaches. Sand back passed from beach sources is assumed to be 100% beach compatible. Source: Coastal Frontiers Corporation, 2000.

7.6). In 1945-46 this new entrance channel was dredged into Alamitos bay providing 800,000 yd^3 of sand to the beaches west (or updrift) of the entrance channel (Wiegel, 1994). Alamitos Bay has not needed any maintenance dredging since its construction (Table 7.2).

The San Gabriel River originally provided an average of 182,000 yd^3 of sand annually to this sub-cell. Due to the damming of this river and the construction of debris basins, it currently only discharges an average of 59,000 yd^3/yr of sand (coarser than 0.0625 mm), which is a reduction of 67% from its natural yield (Willis and Griggs, 2003; Willis et al., 2002).

HUNTINGTON BEACH SUB-CELL: ANAHEIM BAY TO CORONA DEL MAR

Physical Setting: The Huntington Beach sub-cell extends 19 miles from the east jetty of Anaheim Bay to Newport Bay. The majority of this stretch of coast consists of wide, sandy beaches, with the exception of Huntington Cliffs where beaches are narrow to non-existent. The beaches along this stretch of coast are affected by subsidence, the development of Newport Bay and Anaheim Bay, and the historic change in location of the Santa Ana River outlet. Beach nourishment has been an important factor in the widening and stabilization of Surfside-Sunset and West Newport beaches.

During World War II, the U.S. Navy constructed two shore parallel rubble-mound arrowhead jetties forming the entrance to Anaheim Bay (Figure 7.7). This harbor is the site of the 5,256-acre Seal Beach Naval Weapons Station, which was established in 1944. Sand is occasionally forced through the east jetty by wave impact creating a navigational hazard in the harbor that requires maintenance dredging. Anaheim Bay has been dredged four times since 1971 averaging ~144,000 yd^3/yr (Table 7.2).

The beaches from Surfside (Figure 7.8) to Sunset (Figure 7.9) experienced significant erosion after the construction of the jetties at Alamitos Bay in 1933 (Griggs et al., 2005; Patterson and Young, 1989; Wiegel, 1994). This erosion was further aggravated by subsidence (Habel, 1978; Wiegel, 1994). Beach nourishment is required to maintain and stabilize these beaches to meet the recreational needs of the area. The construction of the Naval Weapons Station between 1944 and 1947 provided 1.4 million yd^3 of dredged material, which was placed on the downcoast side of the breakwaters at Anaheim Bay onto Surfside/Sunset beach (Wiegel, 1994)(Table 7.5).

Fig 7.7: Anaheim Bay and the Naval Weapons Station, established in 1944 Copyright © 2002 Kenneth & Gabrielle Adelman

Large-scale nourishment projects are initiated at these beaches because the fill will travel south as littoral drift, and eventually feed Huntington and Newport beaches, where erosion is also threatening back-beach development.

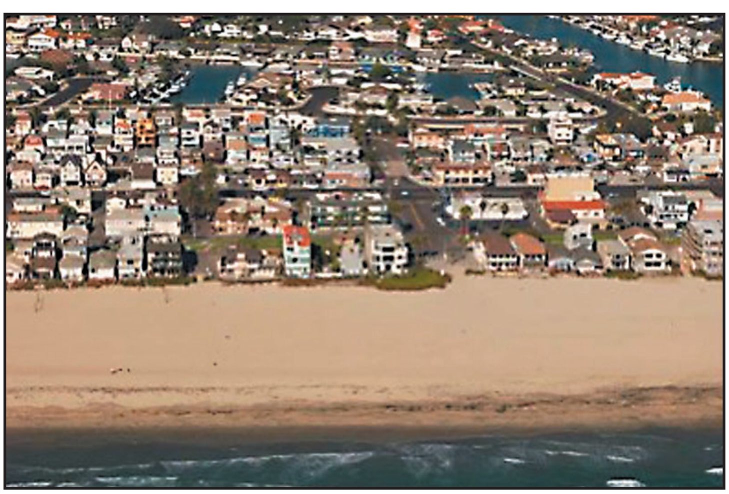

Fig 7.8: Surfside Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

Huntington Beach (along with Santa Cruz) is known as Surf City, USA. It is located on a low Pleistocene bluff and is the only cliffed reach in the San Pedro littoral cell (Figure 7.10). As mentioned previously, nourishment of the Surfside/ Sunset beach has provided sand to this stretch of coast as sand moves downdrift in the southerly direction. Despite the nourishment, these beaches are relatively narrow.

Newport Bay/Harbor was created by excavating a lagoon/wetland area (Figure 7.11). The dredged material was used to widen the beach upcoast of the new harbor (Patterson and Williamson, 1960). Although additional dredging has been done in Newport Bay, the projects were not sponsored by the Corps of Engineers, and the material was apparently not placed on the beaches as nourishment (Wiegel, 1994). Since 1981, an average of ~15,700 yd^3/yr of sand has been dredged from the entrance channel of Newport Bay.

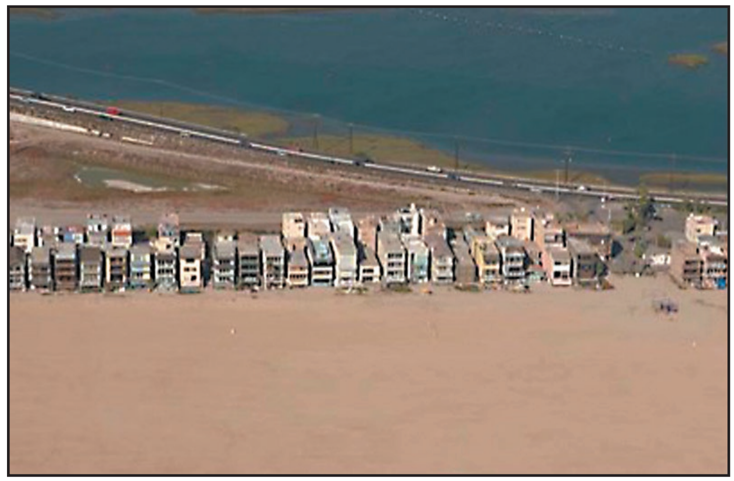

Fig 7.9: Sunset Beach, 2002. Copyright © 2002 Kenneth & Gabrielle Adelman

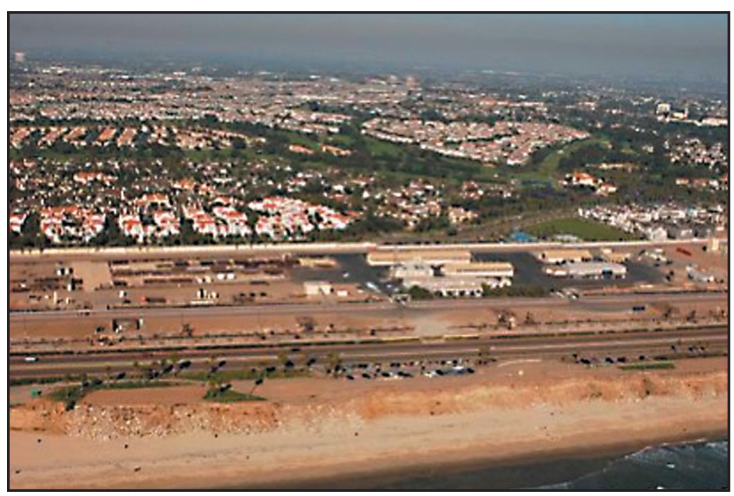

Fig 7.10: Huntington Cliffs, Huntington Beach, California, 2002) Copyright © 2002 Kenneth & Gabrielle Adelman

As a result of severe erosion at West Newport Beach, 8 groins were constructed between 1968 and 1973 (Figure 7.12) in conjunction with a nourishment project which placed a total of 1.8 million cubic yards of sand dredged from the Santa Ana River flood control channel on the beach in this area (Patterson, 1988) (Table 7.5). This project was successful in stabilizing the beach in this area (Walker and Brodeur, 1993; Wiegel, 1994).

Fig 7.11: Entrance to Newport Bay. Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 7.12: Groins at Newport Beach. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND BUDGET FOR THE HUNTINGTON BEACH SUB-CELL

Beach Nourishment: From 1945 to 2002 more than 15 million cubic yards of sand were placed on Surfside-Sunset Beach as part of a nourishment program (personal communication, Los Angeles District USACE; Coastal Frontiers Corporation, 2000), and nearly 3 million cubic yards of sand were placed on West Newport Beach. This nourishment added approximately 375,000 yds^3/yr to the sand budget of this sub-cell (Table 7.5).

River Input: The Santa Ana River (Figure 7.13) is the only significant fluvial source of sand to the Huntington Beach sub-cell. Prior to 1825, the Santa Ana River, originating in the San Bernadino Mountains and flowing across the coastal plain to the ocean, discharged into Anaheim Bay. However, in 1825, extreme flooding caused this river to change its course and shift to the southeast until it eventually discharged near the head

Fig 7.13: Mouth of the Santa Ana River. Copyright © 2002 Kenneth & Gabrielle Adelman

land at Corona del Mar. Charts from 1857 show the river entering the ocean 8,000 feet west of the Corona del Mar headland. In 1861, another major flood caused the mouth of the river to shift again to the base of the headland. Finally in 1920, the river outlet was stabilized with two rock jetties and forced to flow directly into the ocean 5.1 miles updrift of the Corona del Mar headland at the southern end of Huntington State Beach (Patterson and Williamson, 1960; Wiegel, 1994).

The Santa Ana River naturally contributed an average of 379,000 yd^3/yr of sand to this sub-cell. This sand yield has been reduced about 67% through damming, and today provides an average of only ~125,000 yd^3/yr of sand to this littoral cell (Willis and Griggs, 2003; Willis et al., 2002).

Cliff Erosion: Huntington Cliffs (Figure 7.10), extending ~3,800 feet alongshore, are the only coastal bluffs in the Huntington Beach sub-cell. These bluffs are composed predominantly of fine-grained sediment that will not remain on the beaches when eroded. Through sampling and a grain-size analysis, it was determined that only 14% of the bluff sediment is coarser than 3.25Ø and will remain on the beaches. These bluffs only contribute ~2,000 yd^3/yr of sand to the beaches in this sub-cell, on average.

Newport Submarine Canyon: Between West Newport Beach and Balboa Peninsula, Newport Submarine Canyon reaches far enough into the nearshore zone to act as a permanent sink to sand traveling along the shoreline as littoral drift (Coastal Frontiers Corporation, 2000). As previously mentioned, during the past few decades, researchers have concluded that little sand is lost into Newport Canyon (Everts, 1991; Everts and Eldon, 2005; Felix and Gorsline, 1971; Habel, 1978; Wiegel,.1994). Everts and Eldon (2005) estimate that an average of only ~1,000 yd^3/yr is lost into the canyon

Subsidence: As discussed previously, subsidence, or the lowering of ground elevation due to oil or water extrac-

Year	Borrow Site	Placement Location	Volume Dredged (cy)	Adjustment Factor	Approximate Sand Volume Placed
1945	Naval Weapons	Surfside Sunset Beach	1,400,000	0.80	1,120,000
	Station				
1964	Naval Weapons	Surfside Sunset Beach	4,000,000	0.80	3,200,000
	Station				
1971	Naval Weapons	Surfside Sunset Beach	2,260,000	0.80	1,808,000
	Station				
1979	Nearshore Borrow	Surfside Sunset Beach	1,644,000	0.80	1,315,200
	Pit				
1983	Naval Weapons	Surfside Sunset Beach	500,000	0.80	400,000
	Station				
1984	Nearshore Borrow	Surfside Sunset Beach	1,500,000	0.80	1,200,000
	Pit				
1984	Naval Weapons	Surfside Sunset Beach	783,000		600,000
	Station				
1988/89	Naval Weapons	Surfside Sunset Beach	180,000		72,000
	Station				
1990	Nearshore Borrow	Surfside Sunset Beach	1,822,000	0.80	1,458,000
	Pit				
1997	Offshore	Surfside Sunset Beach			1,630,000
1999/00	Naval weapons	Surfside Sunset Beach	330,000		143,000
	station				
2002	Offshore	Surfside Sunset Beach			2,223,000
		Annual Nourishment Rate (cy)	= 268,000	Total Quantity (cy)	= 15,278,000
1965	Balboa Peninsula*	West Newport Beach	124,000	1.00	124,000
1966	Balboa Peninsula*	West Newport Beach	60,000	1.00	60,000
1967	Balboa Peninsula*	West Newport Beach	150,000	1.00	150,000
1968	Balboa Peninsula*	West Newport Beach	495,000	1.00	495,000
1968	Santa Ana River	West Newport Beach	246,000	0.80	197,000
1969	Santa Ana River	West Newport Beach	750,000	0.80	600,000
1970	Santa Ana River	West Newport Beach	124,000	0.80	99,000
1973	Santa Ana River	West Newport Beach	358,000	0.80	286,000
1992	Santa Ana River	West Newport Beach	1,300,000	0.80	1,040,000
		Annual Nourishment Rate (cy/yr)	= 223,000	Total Quantity (cy)	= 13,387,200

Table 7.5: Beach Nourishment at Surfside-Sunset Beach and West Newport Beach, 1945-2002. Adjustment factor refers to the percentage of sand-sized material. Dredged material from rivers is assumed to be 20% fine-grained sediment, which will not remain on the beaches.

* Bypassing from Balboa Peninsula is not included in the total nourishment quantity or the annual nourishment rate because it is an intra-cell movement of sand. Data modified from Coastal Frontiers Corporation, 2000, and Los Angeles District, USACE.

tion, has been a significant sink for sand in the San Pedro littoral cell in general, and for the Huntington Beach sub-cell in particular, since the 1920's (Coastal Frontiers Corporation, 1996; 2000; Griggs et al., 2005; Wiegel, 1994). Subsidence had been documented by Orange County and the cities of Long Beach, Huntington Beach, and Newport Beach through long-term monitoring of benchmark elevations (Coastal Frontiers Corporation, 1996; 2000). The estimated sand loss due to subsidence was reported by Coastal Frontiers Corporation (2000) to average ~72,000 yd^3/yr in this sub-cell (Table 7.6).

Long-Shore Transport: Estimates of longshore transport for the Huntington Beach sub-cell vary widely depending on the research methods used to calculate the rates. Net longshore transport from Surfside/Sunset beach to Newport Bay is to the southeast, diminishing as you progress towards the Santa Ana River; however seasonal reversals do occur. Hales (1980) estimated potential littoral drift using detailed wave statistics. His research concluded that there was net transport to the south at an average, annual rate of 276,000 yd^3 at Surfside-Sunset Beach, 112,000 yd^3 at the Santa Ana River Mouth and 127,000 yd^3 at Newport Beach. This is the rate of sand that could "potentially" be transported by the longshore current if that volume of sand were available. It is not a measure of actual littoral drift, however.

Sub-Reach	Period	Subsidence (ft/yr)	Sand Loss (cy/yr)
Surfside-Sunset	1976-1986	0.0022	1,000
Bolsa Chica	1976-1986	0.0031	2,000
Huntington Cliffs	1976-1986	0.0525	34,000
Huntington Beach	1976-1986	0.0075	12,000
West Newport	1976-1986	0.0119	7,000
Balboa Peninsula	1963-1992	0.0355	16,000
		Total	72,000

Table 7.6: Estimated sand loss due to subsidence in the Huntington Beach sub-cell.

SUMMARY

The sand budget for the San Pedro littoral cell is presented in Figure 7.14. The cell has been broken down into three sub-cells: A. Los Angeles/Long Beach Harbor; B. Seal Beach; and C. Huntington Beach. An additional, alongshore, running budget is provided for the area from Anaheim Bay to Newport Bay (the Huntington Beach sub-cell; Figure 7.15). An alongshore running budget was not developed for the Los Angeles/Long Beach and Seal Beach sub-cells as they are almost completely enclosed behind large breakwaters and there is little useful information that would be provided for such a budget.

The Los Angeles/Long Beach Harbor sub-cell extends from Point Fermin to Alamitos Bay; this entire stretch of coastline is protected from wave action by the breakwaters forming the harbor complex. As a result of these breakwaters, there is little to no alongshore movement of sand in this sub-cell. Sand discharged from the Los Angeles River is the only input of sand, but this sand only serves to clog the harbor. Occasionally, the harbor complex is dredged, averaging ~54,200 yd^3/yr, and the sand used as nourishment for Cabrillo and Long beaches. The remaining sand, 23,000 yd^3/yr, is shown as being stored behind the breakwaters of the harbor complex; however this is only an estimate used to balance the budget.

The Seal Beach sub-cell (Figures 7.1 and 7.14) contains a small stretch of coast extending from Alamitos Bay and the San Gabriel River to Anaheim Bay. Unlike the rest of the San Pedro littoral cell, longshore transport or littoral drift, moves to the northwest in this sub-cell. The San Gabriel River discharges an average of 59,000 yd^3/yr of sand annually, and beach nourishment from outside sources adds an additional 7,000 yd^3/yr of sand to this sub-cell on average. This average does not include sand bypassing operations from West Beach to East Beach because this represents an intra-cell movement of sand, not additional sand to the budget. An average annual sand volume of 66,000 yd^3/yr is either stored on the beaches or lost offshore.

Huntington Beach sub-cell is the largest sub-cell in the San Pedro beach compartment, extending from Anaheim Bay to Newport Bay. The sand budget for this sub-cell is shown as a box-model in Figure 7.14 and as a running mile-by-mile alongshore budget in Figure 7.15. Sand sources include an average annual volume of 125,000 yd^3 from the Santa Ana River, 223,000 yd^3 from beach nourishment, and 2,000 yd^3 of sand is provided through cliff or bluff erosion. Sand sinks for this cell include an average annual volume of ~72,000 yd^3 lost through subsidence and ~1,000 yd^3 lost into Newport Submarine Canyon. Anaheim and Newport bays dredge an average of 144,000 yd^3/yr and 15,700 yd^3/yr respectively. It is assumed that the sand entering these harbors is from the Huntington Beach sub-cell, representing an additional sink. There is a surplus of sand in this cell on the order of 118,000 yd^3/yr that is shown to be partially stored behind retention structures resulting in wider than natural beaches, and, to a smaller degree, partially lost offshore.

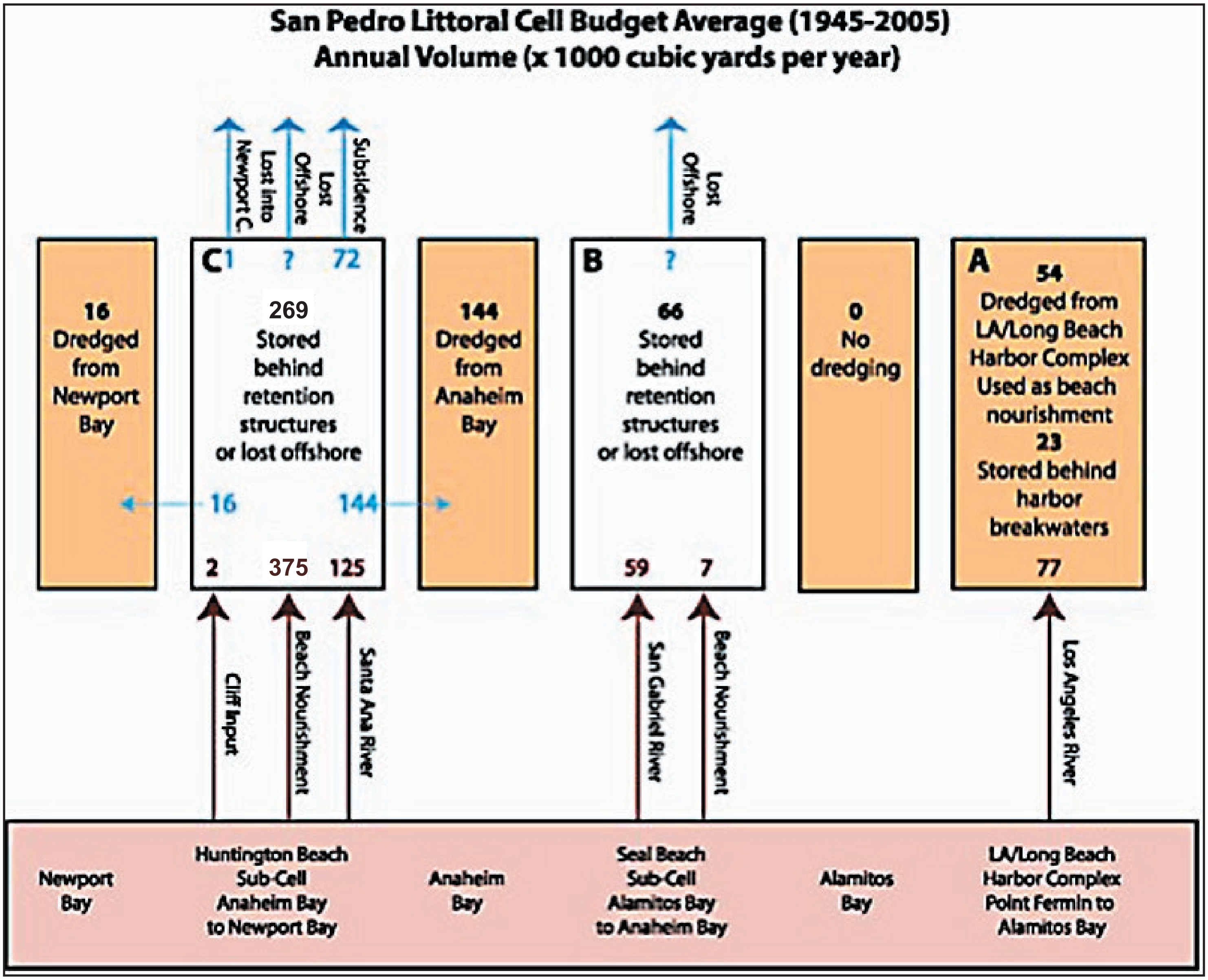

Fig 7.14: Sand Budget developed for the San Pedro littoral Cell from 1945-2005

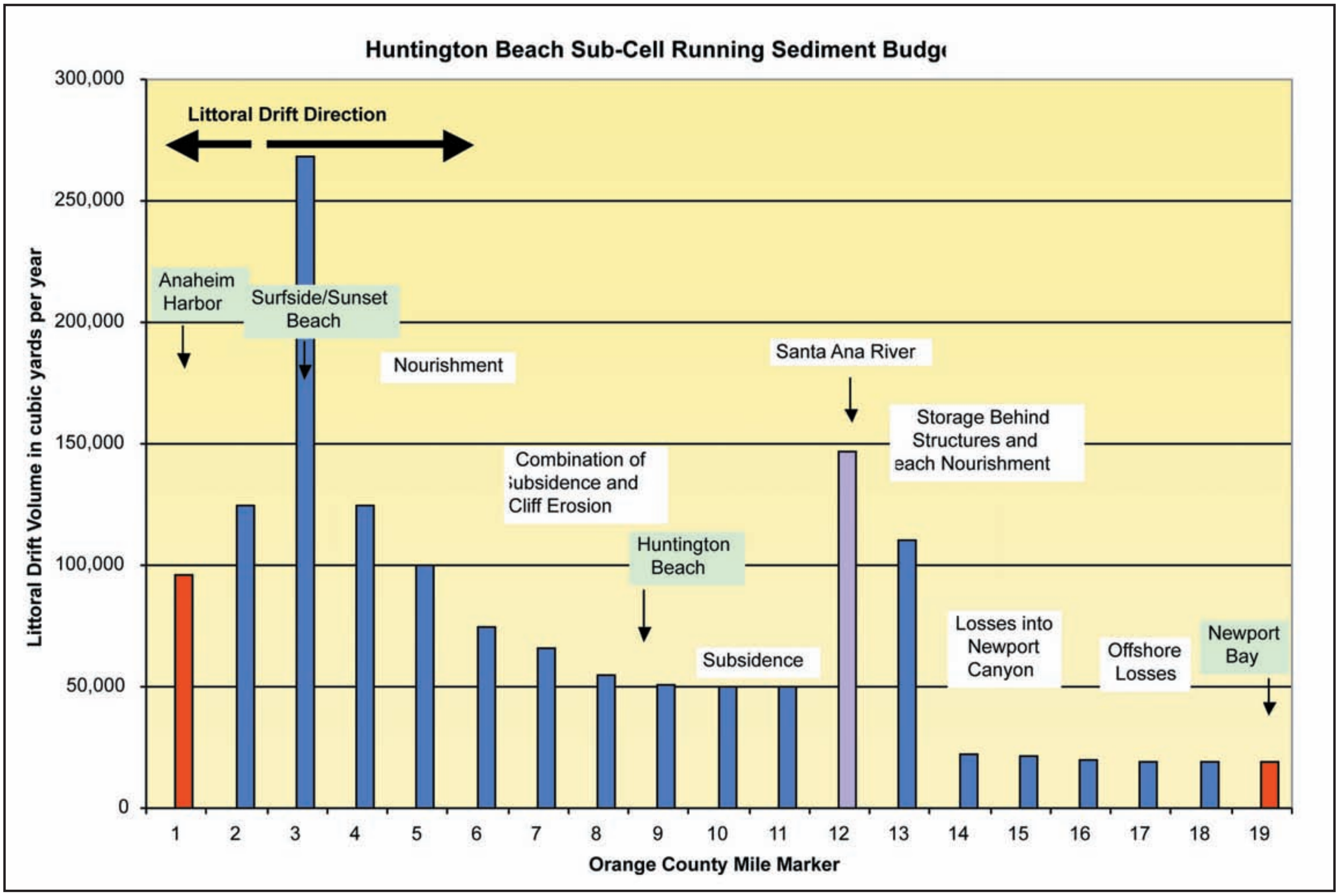

Fig 7.15: Running Budget for the Huntington Beach Sub-cell

Chapter 8

Laguna Littoral Cell Sand Budget

The Laguna littoral cell is 13.4 miles long, and is a combination of sub-cells, or mini-cells, confined between Corona del Mar, which ends the San Pedro littoral cell, and Dana Point (Figures 8.1, 8.2, and 8.3). The San Joaquin Hills reach to the Pacific Ocean creating a rocky coastline consisting of resistant headlands and pocket beaches backed by coastal cliffs or bluffs. These sandy pocket beaches are quite wide in some cases; however, access is limited due to bluff-top development and the rugged nature of the coast. Because these beaches are essentially trapped between headlands, they have been relatively stable over the last 50 years (Coastal Frontiers Corporation, 2000). Unlike the other littoral cells in southern California, the Laguna cell has had little human intervention.

Fig 8.1: Map of the Laguna Littoral Cell

The Laguna littoral cell can be divided into 23 "sub-cells"

(Figure 8.3), or mini-cells. Unlike the sub-cells in the San Pedro littoral cell, these sub-cells are not entirely self-contained; in some cases sand makes it around rocky headlands into the adjacent downdrift sub-cell (Coastal Frontiers Corporation, 2000).

Fig 8.2: Dana Point. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND SOURCES

Rivers: Rivers provide the largest natural source of sand to this region. The three largest streams, Laguna Canyon, Aliso Creek, and Salt Creek (Figure 8.3), provide an average of 1,900 yd^3/yr, 12,000 yd^3/yr, and 1,200 yd^3/yr respectively (Coastal Frontiers Corporation, 2000). Smaller streams and creeks deliver a modest amount of additional sand to each sub-cell. The majority of sand delivered by Aliso Creek (Figure 8.4) is trapped between headlands thus maintaining a stable beach at Aliso Beach (Griggs et al., 2005). Sand discharge from Aliso Creek has decreased from its historic or natural yield due to the infilling of local debris basins and reservoirs; however, this reduction has not been qualified.

The value reported, 12,000 yd^3/yr, is under actual, present-day conditions. Coastal Frontiers Corporation (2000) estimate the average annual sand contribution from rivers and creeks to the entire Laguna littoral cell to be ~18,200 yd^3/yr, accounting for 66% of the sand to the entire littoral cell budget (Table 8.1).

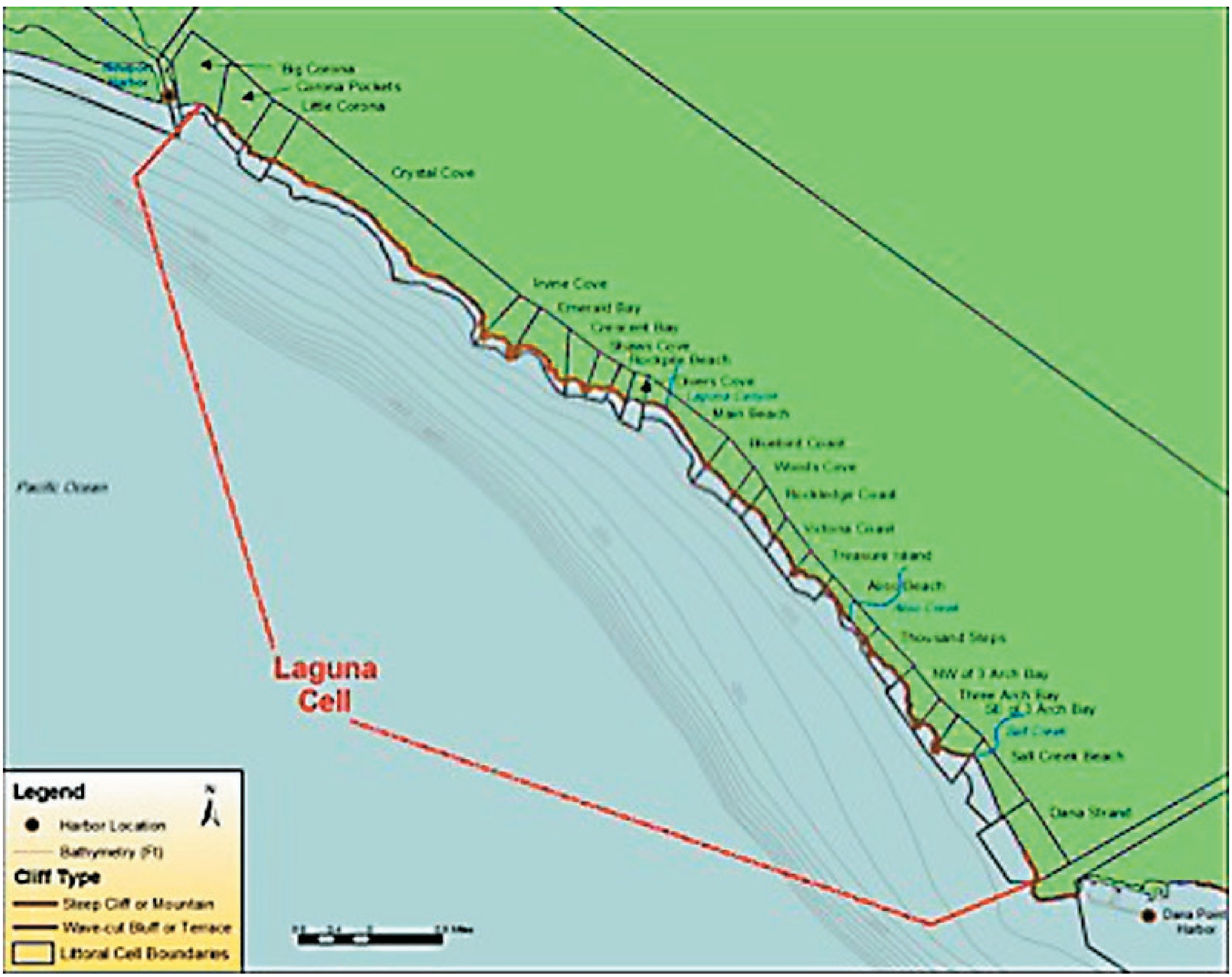

Fig 8.3: Sub-cells and Creeks in the Laguna Littoral Cell

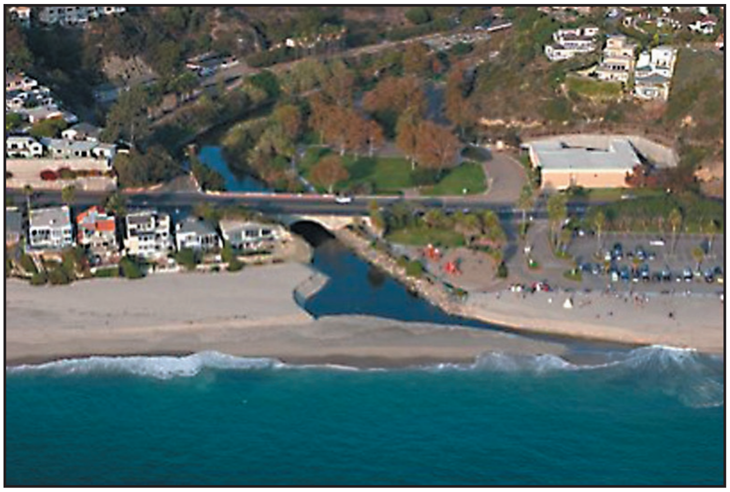

Fig 8.4: Aliso Creek, California. Copyright © 2002 Kenneth & Gabrielle Adelman

Seacliff and Bluff Erosion: Eleven miles of this shoreline are backed by coastal cliffs and bluffs ranging from 15- to 60-feet high with capping terrace deposits up to 15-feet thick; however, cliff erosion rates are minimal due to the resistance of the bedrock forming the cliffs (Griggs et al., 2005). Between Laguna Beach and Dana Point the coastal cliffs and bluffs consist of sandstone with varying degrees of resistance to wave erosion. Retreat rates for the seacliffs along the shoreline of the entire Laguna cell are quiet low and range from 0.07 ft/yr to 0.2 ft/yr (Everts, 1995). Cliff erosion was found through this investigation, to contribute an average of ~8,400 yd^3 of sand annually, representing 31% of the overall sand contribution to this cell (Table 8.1). This estimate is in very close agreement with that found by Coastal Frontiers Corporation (2000) of ~7,900 yd3/yr. Shoreline armoring along a portion of the cliffs has reduced the original, or natural, sand contribution of ~9,700 yd^3/yr by 13%, or 1,200 yd^3/yr (Table 8.1).

Laguna Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers Bluff Erosion Beach Nourishment	18,200 (65%) 9,674 (35%) 0 (0%)	18,200 (66%) 8,400 (31%) 1,000 (4%)	0 (0%) 1.274 (13%) +1,000 (0%)
Total Littoral Input	27,854 (100%)	27,600 (100%)	239 (1%)

Table 8.1: Overall sand contributions and reductions to the Laguna littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

Beach Nourishment: Beach nourishment has not been routinely practiced in the Laguna littoral cell. Modest amounts of sand were, however, placed in the Big Corona sub-cell (Figure 8.3) from the construction and maintenance of Newport Harbor (considered in this report to be within the San Pedro littoral cell; Habel and Armstrong, 1978). Coastal Frontiers Corporation (2000) estimated a value of 1,000 yd^3/yr of nourishment added to the sand budget in this cell. Their estimate was adopted for this report. Thus, beach nourishment provides ~4% of the sand to the overall littoral budget in the Laguna littoral cell (Table 8.1).

SAND SINKS

Offshore Losses: Because of the crenulated nature of the shoreline and the fact that there are no submarine canyons reaching into the nearshore zone, the largest sink for sand in the Laguna littoral cell is the inner shelf. Coastal Frontiers Corporation (2000) estimated offshore losses by analyzing bathymetric survey data from 1934 and 1975, as well as sand tracers and shoreface slopes. Their findings indicate that the Big Corona sub-cell had a net gain of sand in the inner shelf derived from the offshore region. Rockledge and NW Three Arches Bay had no change in the offshore profiles indicating a zero net transport between the on- and off-shore zones; the rest of the sub-cells lost sand from the inner shelf to offshore. The total flux of sand in all sub-cells is estimated to be an average of ~1,600 yd^3/yr seaward, representing a sink for sand in the littoral budget (Coastal Frontiers Corporation, 2000).

LONGSHORE TRANSPORT

Littoral drift along most of the shoreline in the Laguna littoral cell is interrupted by headlands and trapped in pocket beaches. Alongshore transport rates increase where there is a sand source, such as Aliso Creek, followed by a less crenulated shoreline where the sand has a chance to move downdrift with less interruption by rocky headlands. In these stretches of uninterrupted shoreline, net littoral drift is to the south. Littoral drift had been estimated to be approximately 1,000 yd^3/yr to the south from Newport Harbor to Aliso Creek, increasing to approximately 15,000 yd^3/yr from Aliso Creek to Dana Point Harbor (Coastal Frontiers Corporation, 2000). These rates are low due to the minimal volume of sand available for transport along this stretch of shoreline. Potential littoral transport rates may be greater; however, with a lack of sand available for transport, the potential is not met, which may result in beach erosion.

SUMMARY

The sand budget for the Laguna littoral cell is shown in Figure 8.5 (on following page). Small sand volumes dominate all sources and sinks for this cell. Due to the crenulated nature of the shoreline, the Laguna littoral cell is broken into 23 mini-cells or "leaky" sub-cells (Figure 8.3). Sand is supplied to this cell from creeks, seacliff or bluff erosion, and beach nourishment. Offshore losses are the main sink for sand. Storage of sand occurs within the sub-cells in pocket beaches, which tend to be stable because the sand is trapped between two headlands. Sand supplied to the beaches through seacliff or bluff erosion has been reduced by ~13% due to coastal armoring; however, this reduction is offset by beach nourishment. Overall, there has been a 1% reduction to the natural sand supply in the Laguna littoral cell when considering beach nourishment as a source of sand in the overall budget. Littoral drift and sand transport between adjacent cells is modest where the beaches are confined between headlands. Sand transport rates alongshore between sub-cells increases south of Aliso Creek (Figure 8.4). Overall, the beaches in the Laguna littoral cell are stable.

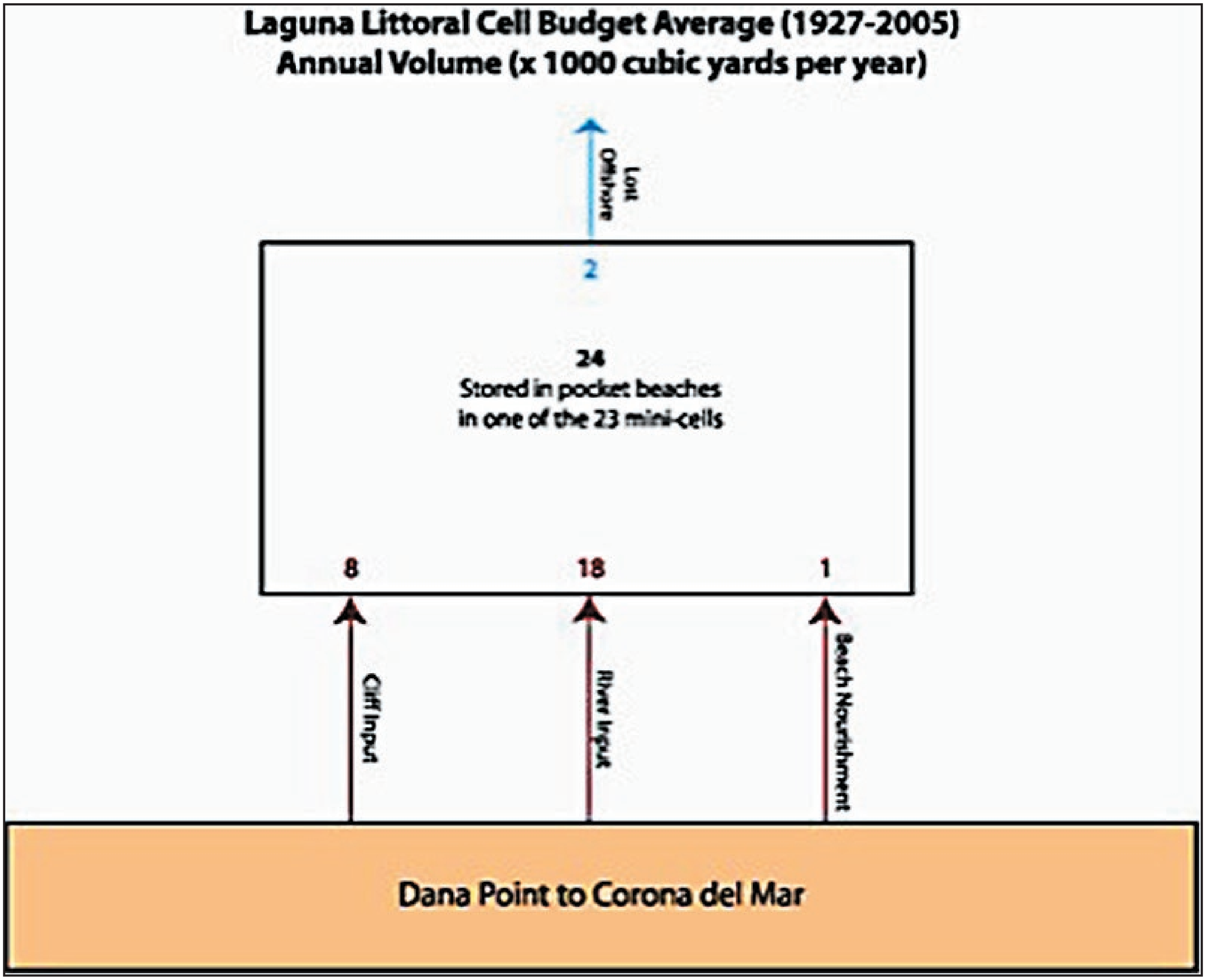

Fig 8.5: Sand Budget for the Laguna Littoral Cell

Chapter 9

OCEANSIDE LITTORAL CELL SAND BUDGET

The Oceanside littoral cell (Figure 9.1) extends approximately 50 miles from Dana Point Harbor south to La Jolla and Scripps Submarine Canyons (Habel and Armstrong, 1978; Inman and Frautschy, 1966; Robinson, 1988). The shoreline of this cell consists of a continuous, narrow beach backed by seacliffs or bluffs with the exception of the mouths of coastal rivers and streams. Rocky headlands form the northern and southern boundaries of this cell. The coastal towns of Encinitas and Solana Beach have suffered severe bluff erosion resulting in property damage. Extensive seacliff armoring has been installed over the years in an attempt to halt bluff erosion and protect bluff-top development.

SAND SOURCES

Fluvial Sources: San Juan Creek and the Santa Margarita, San Luis Rey and San Dieguito rivers are the major sources of fluvial sand to the Oceanside littoral cell. San Juan Creek and the Santa Margarita and San Luis Rey rivers each contribute on average ~40,000 yd^3/yr of sand, while the San Dieguito River contributes an average of ~12,500 yd^3/yr of sand to the littoral budget (sediment coarser than 0.0625 mm) (Willis et al., 2002). The Santa Margarita, San Luis Rey and San Dieguito rivers have had their natural sand yields reduced by 31%, 69% and 79%, respectively, (a reduction of ~154,000 yd^3/yr) through damming (Table 9.1)(Willis et al., 2002). Fluvial sources originally provided ~66% of the sand to this littoral cell. Post-damming, the rivers now provide only ~33% of sand to the overall littoral cell budget (Table 9.1).

Sand transport to the coast from these rivers is highly episodic as a function of rainfall duration and intensity. Wiegel (1994) sites a report by Tekmarine (1987), stating that the last time the Santa Margarita and San Luis Rey river mouths were sufficiently breached as to allow a significant volume of sand to be transported into the littoral zone was in 1969 (the time before that was 1941).

Cliff Erosion: Seventy-three percent of the Oceanside littoral cell consists of eroding seacliffs that range in height from 25 to 100 feet with the notable exception of the Torrey Pines area where cliffs reach heights of over 300 feet (Runyan and Griggs, 2002). At most locations in the Oceanside cell, the seacliffs consist of two units: relatively resistant Eocene bedrock, composed of a variety of sedimentary rocks ranging from mudstone to sandstone and conglomerate, and a capping unit of unconsolidated Pleistocene marine terrace material. Once eroded, the bedrock and terrace deposits provide a wide range of grain sizes to the littoral budget. By analyzing the grain size distribution of sand on nine beaches in the Oceanside Cell, the littoral cut-off diameter was determined to be approximately 0.088 mm (3.5Ø). Annual cliff erosion rates in this littoral cell, determined by Benumof and Griggs (1999) and Moore et al. (1998) and expressed as weighted averages for distinct segments of the cell, vary from ~0.4 inches to about 8 inches per year depending on the bedrock type, rock strength and structural weaknesses, wave climate, and terrestrial processes.

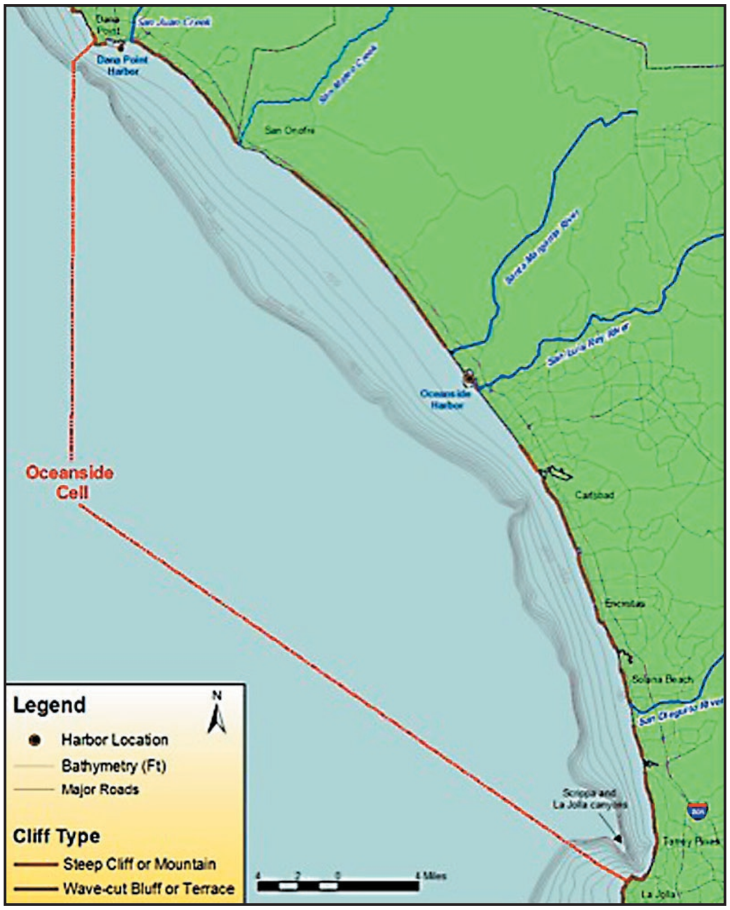

Fig 9.1: Location map for the Oceanside littoral cell

Using the littoral cut-off diameter of 0.088 mm, Runyan and Griggs (2002) determined from a grain size analysis of samples collected from the cliff bedrock and terrace deposits that these units contain, on average, about 51% and 57% respectively, of littoral-size material which contributes directly to the coastal beaches.

Using the area of eroding cliff (linear extent and height or thickness of both the bedrock and terrace deposits taken from field measurements), multiplying this by the average percentage of littoral-size material in each geologic unit, and the average annual erosion rates calculated by Benumof and Griggs (1999) and Moore et al. (1998), Runyan and Griggs (2002) determined that the "natural" cliff contribution of sand to the beaches of the Oceanside cell (without taking into account the reduction of sand due to armoring structures) was approximately 67,300 cubic yards per year.

About twenty percent of the seacliffs in the Oceanside cell have some sort of protective armoring. Assuming the armor is 100% efficient at preventing seacliff erosion, armoring prevents approximately 12,400 cubic yards per year, or 18%, of the "natural" cliff contribution of sand-size material from entering the littoral cell (Runyan and Griggs, 2002). Thus the work of Runyan and Griggs, using the erosion rates developed by Benumof and Griggs (1999) concluded that about 55,000 yds^3 of littoral sized sand is presently being contributed to the beaches from cliff and bluff retreat.

Very recent and more detailed work (Young and Ashford, 2006) has re-evaluated the contributions of the seacliff and gully erosion to the beach sand budget in the Oceanside littoral cell using airborne LIght Detection And Ranging (LIDAR). Seacliff and gully/terrace beach-sediment contributions were compared to coastal stream beach-sediment contributions from previous studies. This study took place over a relatively dry 6-year period extending from April 1998 to April 2004. The results indicate that during this period seacliffs of the Oceanside Littoral Cell provided about 100,000 yds^3 (76,900 m^3) of littoral sized sand to the shoreline, almost twice as much as the earlier and less site-specific work of Runyan and Griggs (2002) and earlier values determined by Everts (1990) of 41,600 yds^3 (32,000 m^3).

Young and Ashford also reexamined the previous reports on littoral sediment contributions for gully erosion and terrace degradation used in earlier littoral budgets. Gullies yielded 26,000 yds^3 of sand annually during the study period, which is significantly lower than the rates reported by Robinson (1988) and used in previous budgets. Robinson's study covered a time period during which several severe gully events occurred as a result of altered drainage patterns associated with construction of the coastal highway. The gully erosion measured by Young and Ashford (2006) did not compare to the large gully events included in the Robinson study. Young and Ashford recommend that the average annual gully beach-sediment contributions reported in previous studies be reconsidered for future work unless more severe gullying events occur in the future. We have chose to use the more recent and site-specific work reported in Young and Ashford (2006) in our Oceanside Littoral Cell budget.

Comparison of their results to previous studies suggests that the relative seacliff sediment contributions may be significantly higher than previously thought (25% of the present-day littoral budget; Table 9.1). Again, beach-sediment contributions from gullies and terrace erosion were significantly lower compared with previous studies. This may in part be due to the episodic nature of gullying and the relatively dry study period used by Young and Ashford.

Gully and Terrace Degradation: Additional sand inputs that have been considered in the past to be important to the Oceanside littoral cell include gully and upland terrace erosion or degradation (Kuhn and Shepard, 1984; Robinson, 1988; Runyan and Griggs, 2002). However, as explained above, more recent work by Everts (1990) and Young and Ashford (2006) has been used instead. Based on their shorter-term but more detailed investigation, the contributions of gully erosion and terrace degration total ~31,500 yds^3 of sand annually, or about 7% of the present-day littoral budget for the cell (Table 9.1).

Beach Nourishment: There are two harbors in this littoral cell, Dana Point Harbor, located at the northern end of the cell (Figure 9.2), and Oceanside Harbor (Figure 9.3), located in the middle of the cell. Only Oceanside Harbor requires maintenance dredging and it may be used as an indicator of longshore transport, although there are many complications in the Oceanside cell at this location; the harbor also provides sand for downdrift nourishment. Dana Point Harbor is located at the upcoast, or northernmost point, of the littoral cell, and because of this location at the node between two cells, has not required maintenance dredging since its construction.

Construction began on the Oceanside Harbor in 1942 with the U.S. Marine Corps' Del Mar Boat Basin. In 1958, its breakwater was extended, and in 1962 the adjacent Oceanside Small Craft Harbor facility was completed, along with another extension of the breakwater. Oceanside Harbor has required routine maintenance dredging since 1963 (Table 9.2). Disposal of dredged material has been used to mitigate the erosion of the downdrift beaches resulting from the construction of the harbor.

In addition to the sand provided by the dredging of Oceanside Harbor, sand was added to the littoral budget in the Oceanside cell from the dredging of Agua Hedionda Lagoon (~4 million cubic yards). Smaller projects such as the construction of the San Onofre Nuclear Generating Station, from 1964-1985, provided an additional ~1.1 million cubic yards of sand to the beaches (Flick, 1989; Wiegel, 1994).

Doheny Beach State Park, located updrift of Oceanside Harbor, was nourished in two increments with sand obtained from San Juan Creek and from local marine terrace deposits (Wiegel, 1994). The downdrift portion of the beach, located 4,500 feet from San Juan Creek, was nourished with 690,000 cubic yards of sand trucked in from old terrace deposits at Camp Pendleton in 1966 (Shaw, 1980; USA/CESPL, 1965; Wiegel, 1994). The second part of the nourishment project took place on the beaches between Dana Point Harbor's east breakwater and the jetty on the north side of San Juan Creek. In 1964, 94,000 cubic yards of sand, obtained from San Juan Creek, were placed on these beaches (Wiegel, 1994). To maintain the fill, the San Juan north jetty was constructed. This project formed a pocket beach 1,400-feet-long, which is still heavily used today, and changed the beach from a cobble and rock beach to a sandy beach (Wiegel, 1994).

Oceanside Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	286,500 (66%)	132,500 (33%)	154,000 (54%)
Bluff Erosion	118,000 (27%)	100,000 (25%)	18,000 (15%)
Gully/Terrace Erosion	31,500 (7%)	31,500 (7%)	0 (0%)
Beach Nourishment		138,000 (34%)	+138,000 (0%)
Total Littoral Input	435,700 (100%)	401,700 (100%)	34,000 (8%)

Table 9.1: Overall sand contributions and reductions to the Oceanside littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment.

In 1982, 1.3 million cubic yards of sand were trucked in from the San Luis Rey river bed to nourish the severely eroding beaches at Oceanside (Flick, 1994; Wiegel, 1994). In total, beach nourishment (not including bypassing from Oceanside Harbor) has provided ~7.2 million cubic yards of fill on the beaches in this cell, which is ~138,000 yd^3/yr over the last 65 years (1940-2005), representing 34% of the sand in the overall littoral budget (Table 9.1).

More recently, approximately two million yds^3 of sand were dredged from six offshore sites and placed on the beaches of San Diego County (Patsch and Griggs, 2006). This project was coordinated by local governments working together through SANDAG and was funded by $16 million in state and federal funds and about $1.5 million from the region's coastal cities. It was seen as an initial step in overcoming what has been perceived as a severe sand deficit on the region's beaches. A total of six miles of beaches were nourished from Oceanside on the north to Imperial Beach on the south. About eighty-five percent of the sand (1,780,000 yds^3) went to the beaches of the Oceanside Littoral Cell. This volume was added to the historic 65-year nourishment volumes included in Table 9.1.

Interestingly, although there has been a reduction of about 54% in the littoral sand input to the Oceanside Cell, this was not a source of large amounts of sand under natural conditions (Table 9.1). The average annual nourishment over the past 65 years has nearly made up for much of the reduction from stream damming such that the total budget for the cell has only been reduced by about 8 percent. While the budget appears nearly balanced on an average annual basis (Table 9.1), with the exception of the 2001 SANDAG nourishment project most of the historic nourishment took place several decades ago so there is still appears to be a significant reduction in sand input to the cell compared to the original natural conditions.

SAND SINKS

Submarine Canyons: Sand entering the Oceanside littoral cell moves southward in the direction of the net alongshore transport and eventually enters the heads of La Jolla and Scripps submarine canyons (Figure 9.1), which are within a few hundred yards of the shoreline, just offshore from Scripps Institution of Oceanography (Inman, 1976). These canyons extend offshore in a southwesterly direction for approximately 33 miles, eventually depositing sediment into San Diego Trough, although it is widely believed that La Jolla Submarine Canyon is not a functioning sink for beach sand at the present time.

Dunes: Sand lost to inland dunes is not a significant factor in the Oceanside cell (Flick, 1994).

Offshore Bar: Dolan et al (1987), by comparing National Ocean Survey Sheets for 1934 and 1971-72, found an offshore bar near the entrance to Oceanside Harbor: "The accretion band extends offshore for about 1.5 miles near Oceanside Harbor and then turns parallel to the existing bottom contours at depths between 40 and 60 ft." This pattern of accretion indicates offshore deflection of littoral sand by the harbor's north breakwater, and subsequent southerly transport induced by a coast-parallel current outside the surf zone. According to Dolan et al. (1987), the total offshore deposition translates into an average annual accretion rate of ~144,000 yds^3/yr, if the deposition dates back to the initial construction of the Del Mar Boat Basin in 1942. Dolan et al. also believe that the gross drift arriving from the south may be partially deflected offshore as well. It had been hypothesized by many researchers (Dolan et al., 1987; Inman and Jenkins, 1985; Wiegel, 1994) that this offshore bar is a major sink for sand in this cell. For the purposes of this study, the offshore bar is used to balance the sand budget for the northern reach of the Oceanside littoral cell. Consistent with the findings of Dolan et al (1987) ~144,000 cubic yards per year is shown as moving offshore to be stored in the sandbar.

SAND BUDGET SUMMARY FOR THE OCEANSIDE LITTORAL CELL

The Oceanside littoral cell will be divided into two subcells for this study—Dana Point to Oceanside Harbor, and Oceanside Harbor to the La Jolla and Scripps submarine canyons.

Dana Point to Oceanside Harbor: Dana Point Harbor, constructed in 1970, is situated at the extreme northern end of the Oceanside littoral cell. Since its construction, the harbor has never been dredged for maintenance or navigational purposes. Because it is at the northern tip of a littoral cell with southward-directed littoral drift, and there is little to no sand entering the cell from the rocky stretch of shoreline to the north, this harbor does not act as a sand trap (Griggs, 1987b; Wiegel, 1994). Dana Point Harbor is situated in an ideal location in terms of its position within a littoral cell to avoid the problem of maintenance dredging characteristic of many harbors in California.

Just downcoast of Dana Point Harbor, San Juan Creek (Figure 9.2) enters the ocean, and sandy beaches begin to appear. Littoral drift carries this sand southward until it is joined with the sand from San Mateo Creek and the Santa Margarita River. Combined, these fluvial sources add ~80,000 yds^3/yr of sand to the littoral system (Willis and Griggs, 2003; Willis et al., 2002). Seacliff erosion from this stretch of coast provides an additional ~69,000 yds^3/yr of sand (Young and Ashford, 2006). Gully and upland terrace erosion, provide an additional ~31,500 yds^3/yr. Artificial beach nourishment provides an additional ~110,000 cubic yards per year of sand to the littoral budget. These sand sources combined supply this stretch of the Oceanside littoral cell with ~290,000 yds^3/yr of sand (Figure 9.4 and 9.5). For the purposes of this study, the offshore bar (seaward of Oceanside Harbor) is used to balance the sand budget for the northern reach of the Oceanside littoral cell. Consistent with the findings of Dolan et al (1987), ~144,000 cubic yards per year is shown as moving offshore to be stored in the sandbar. The remaining ~146,000 yds^3 of sand being transported as littoral drift ends up in the entrance channel of Oceanside Harbor where it is dredged and bypassed to the downdrift, or southerly, beaches.

Longshore Transport: At least five studies have attempted to calculate alongshore transport rates within the Oceanside littoral cell. Marine Advisors (1960) used available wave data and calculated a net southerly longshore transport rate of 215,000 yds^3/yr. Following harbor construction, the accretion rate of sand in the harbor entrance was measured along with the associated loss of sand from Oceanside Beach, downcoast of the harbor. Based on entrance channel dredging and downcoast beach erosion, Inman (1976) concluded that the net longshore transport of sand along the shoreline of the Oceanside littoral cell is about 250,000 yds^3/yr to the south.

Hales (1979) and Inman and Jenkins (Inman and Jenkins, 1985) using wave statistics and potential littoral drift theory described in the Shore Protection Manual (USACOE, 1984), determined that an average of 740,000 cubic yards of sand annually are directed to the south and ~550,000 yds^3 of sand are directed to the north per year. This gives an average gross transport rate of ~1,290,000 yds^3 of sand per year, and an average net southward transport rate of ~194,000 yds^3 of sand annually (Dolan et al., 1987). Seymour and Castel (1985) used continuous directional wave measurements immediately south of the harbor to estimate net sand transport over a one-year period (1980) to be about 6500 yds^3 to the north. All of these are potential littoral drift values and are calculated using the wave energy flux approach. These are maximum possible transport rates, independent of sand supply. These calculations are also extremely sensitive to nearshore bathymetry which will determine the amount of wave refraction and therefore the amount of wave energy directed alongshore. The net transport rate found by the longer-term studies (194,000 yds^3/yr to the south) is somewhat lower than the littoral drift calculated from 38 years of dredging history recorded at Oceanside Harbor (averaging 220,000 yds^3/yr).

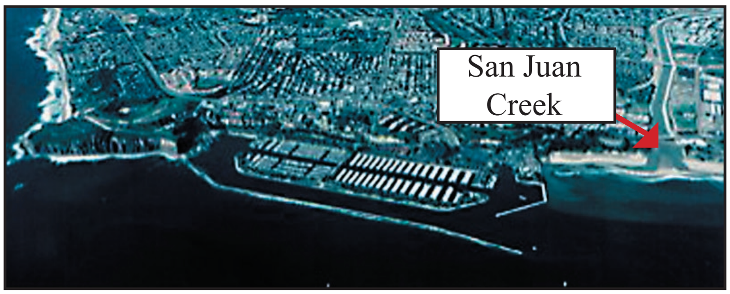

Fig 9.2: Dana Point Harbor and San Juan Creek

Based on the influx of sand to the cell upcoast of the Oceanside harbor (~290,000 yds^3/yr), the offshore accumulation of sand in the large bar (~144,000 yds^3/yr), the dredging history at the entrance to Oceanside Harbor (220,000 yds^3/yr), the net littoral drift near Oceanside Harbor is considered to be ~146,000 yds^3/yr in a downcoast or southeasterly direction. The difference between this value and the average annual dredging volume (220,000 yds^3/yr) is ~74,000 yds^3/yr and is considered to be the average net volume of sand that is transported in a northerly or upcoast into the harbor entrance.

Fig 9.3: Oceanside Harbor

Oceanside Harbor to La Jolla/Scripps Submarine Canyon: South of the Oceanside Harbor the majority of sand, ~50,000 cubic yards per year, is supplied by fluvial sources—the San Luis Rey and San Dieguito Rivers (Willis et al., 2002). Seacliff erosion, resulting mostly from the erosion of the cliffs in the Torrey Pines area, provides an additional ~44,000 yds^3/yr of beach-sand-sized material (0.088 mm or coarser). From the previous discussion regarding balance of transport at the Oceanside harbor, it appears that on average, about 74,000 yds^3 of the ~220,000 yds^3 dredged on average from the Oceanside Harbor annually is transported upcoast into the harbor by littoral drift from the south. Combining these volumes (~40,000 yds^3/yr from streams, ~44,000 yds^3/yr from cliff erosion, and 146,000 yds^3/yr net downcoast littoral drift at Oceanside Harbor) yields an average of ~226,000 yds^3/yr that is added to the beaches between Oceanside Harbor and Scripps Submarine Canyon (Figures 9.4 and 9.5).

There was no significant beach nourishment in this part of the cell until the 2001 SANDAG project added 1,780,000 yds^3 on the beaches south of the harbor. The littoral sand remaining in the system is eventually lost into the Scripps Submarine Canyon (Figure 9.1).

While developing a conceptual model of a littoral cell, such as the Oceanside Cell, with its inputs, outputs, littoral drift and storage is relatively straightforward, attempting to average out the often very large year-to-year fluctuations and produce a quantitative budget is extremely difficult. Those who have studied individual coastal areas or specific littoral cells understand the uncertainties involved. Thus any littoral cell budget is a best estimate based on all accessible information and some judgement calls. Thus while we can calculate a net littoral transport at the Oceanside Harbor of 146,000 yds^3/yr, there are large year-to-year variations, and changes in patterns over time. Richard Seymour of the Scripps Institution of Oceanography (written communication), has observed, for example, that the Oceanside Harbor is not a perfect sediment trap and:

- preferentially bypasses fine-grained sand and traps coarse sand when transport is from the south.
- is a trap for the bypassed sand when it moves north in the summer
- is shoaled by fine sand, which is then dredged and deposited to the south and is then available to be transported back into the harbor
- sees a very small net transport as the difference between two significant directional transport rates

Thus any littoral cell budget needs to be seen as a work in process complicated and made more difficult by annual variations, uncertainties in measuring and/or quantifying each of the individual components, and human impacts to each of the individual processes and components.

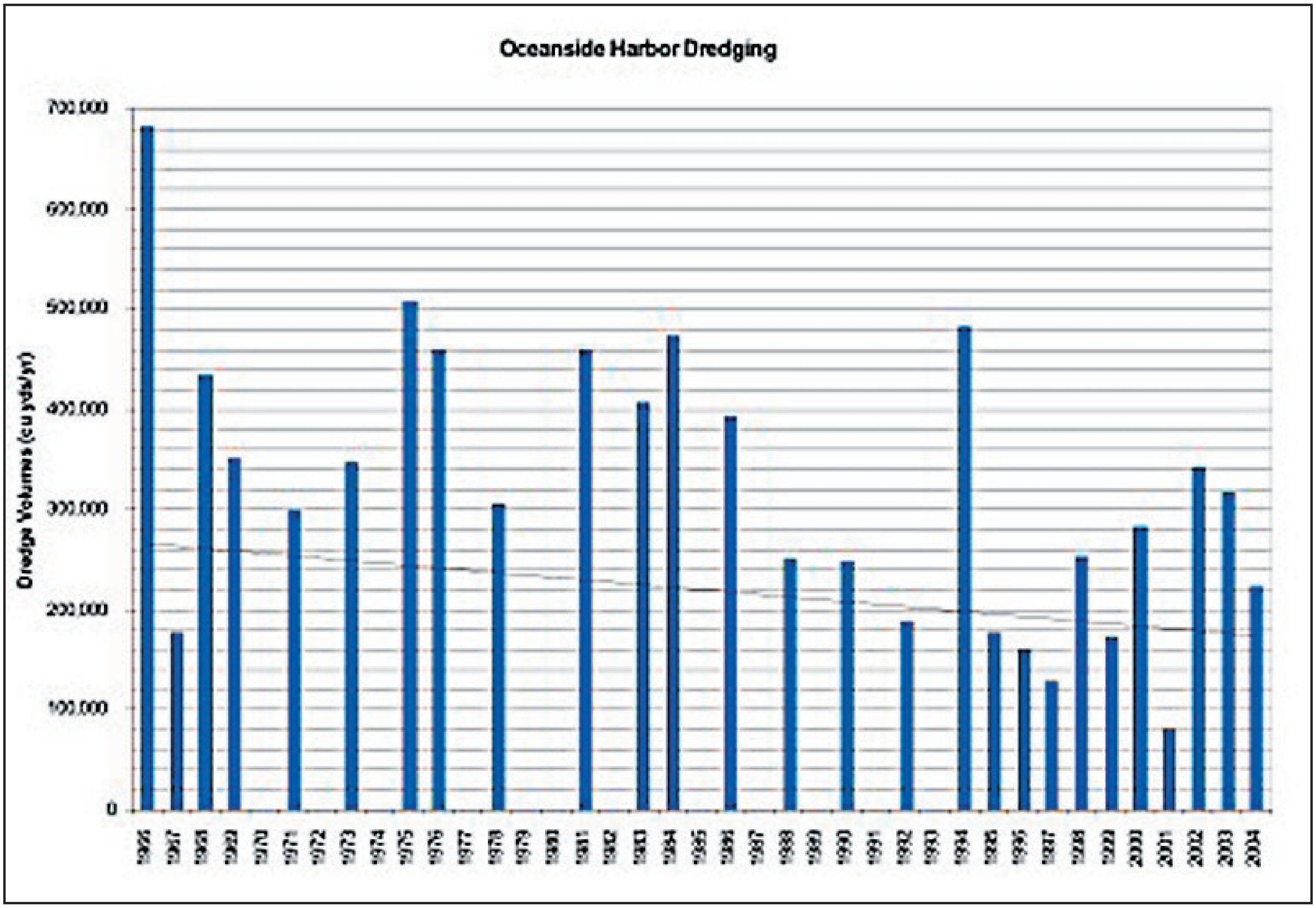

Table 9.4: Annual maintenance dredging volumes for Oceanside Harbor. Average maintenance dredging in the entrance channel from 1966-2004 is ~220,000 yd^3/yr. (Chang, 2001; 2005)

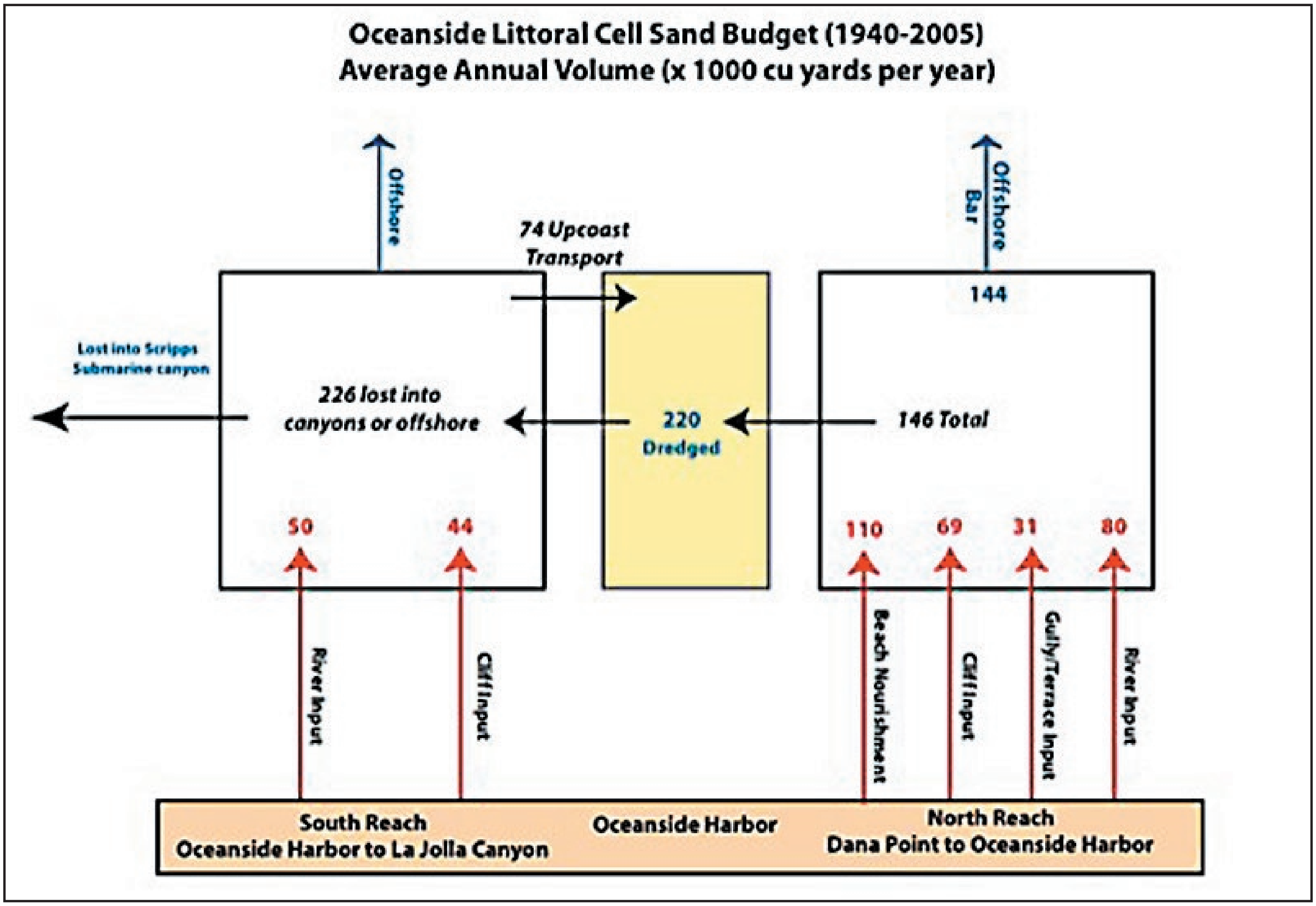

Fig 9.4: Sand Budget for the Oceanside Littoral Cell

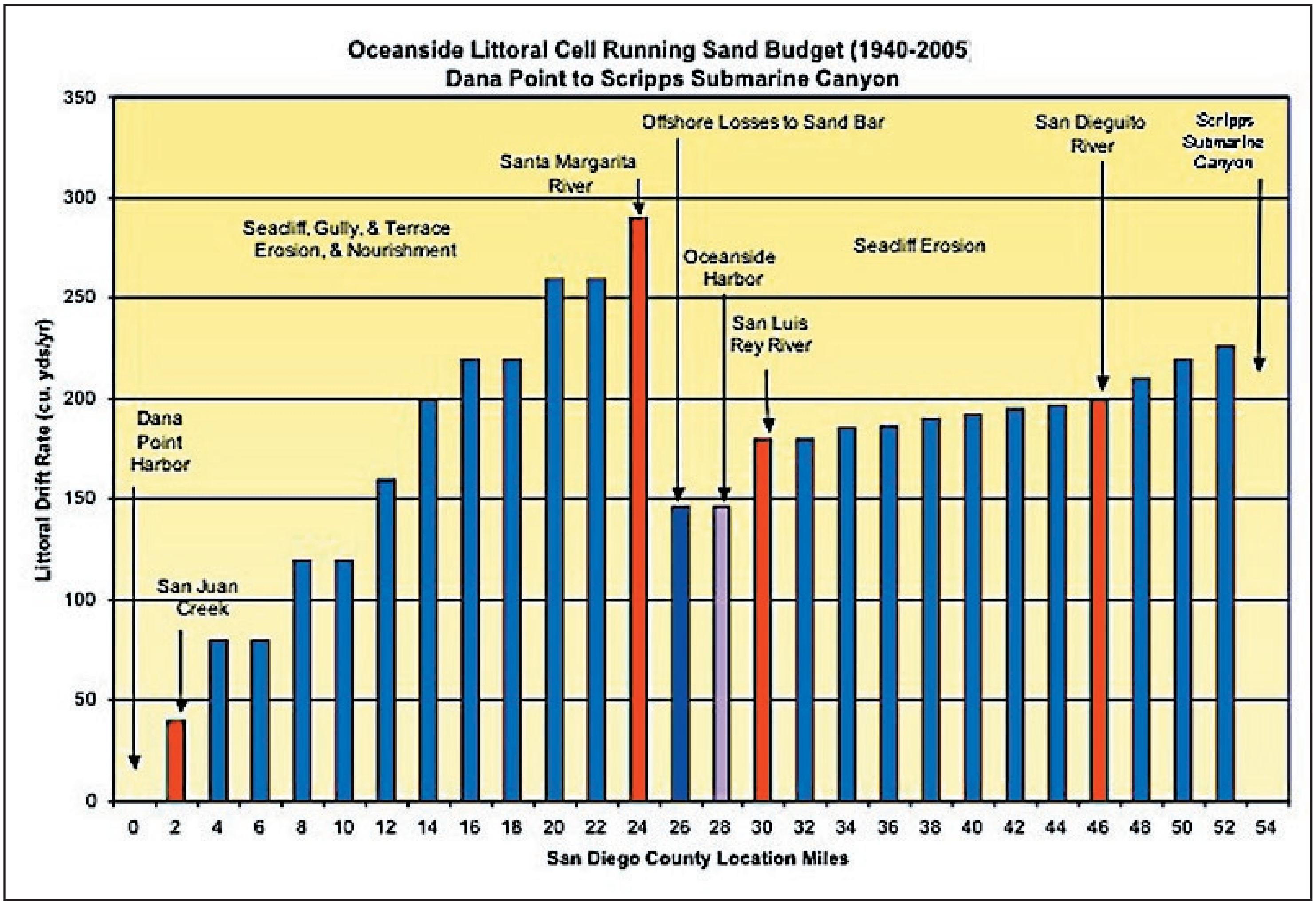

Fig 9.5: Running, mile-by-mile sand budget for the Oceanside littoral cell (no nourishment included)

Chapter 10

MISSION BAY LITTORAL CELL SAND BUDGET

Mission Bay littoral cell (Figure 10.1) is a north-south oriented shoreline extending 14 miles from Point La Jolla to Point Loma. The shoreline in this stretch of coast is characterized by coastal cliffs and bluffs with pocket beaches in addition to moderately wide, sandy beaches.

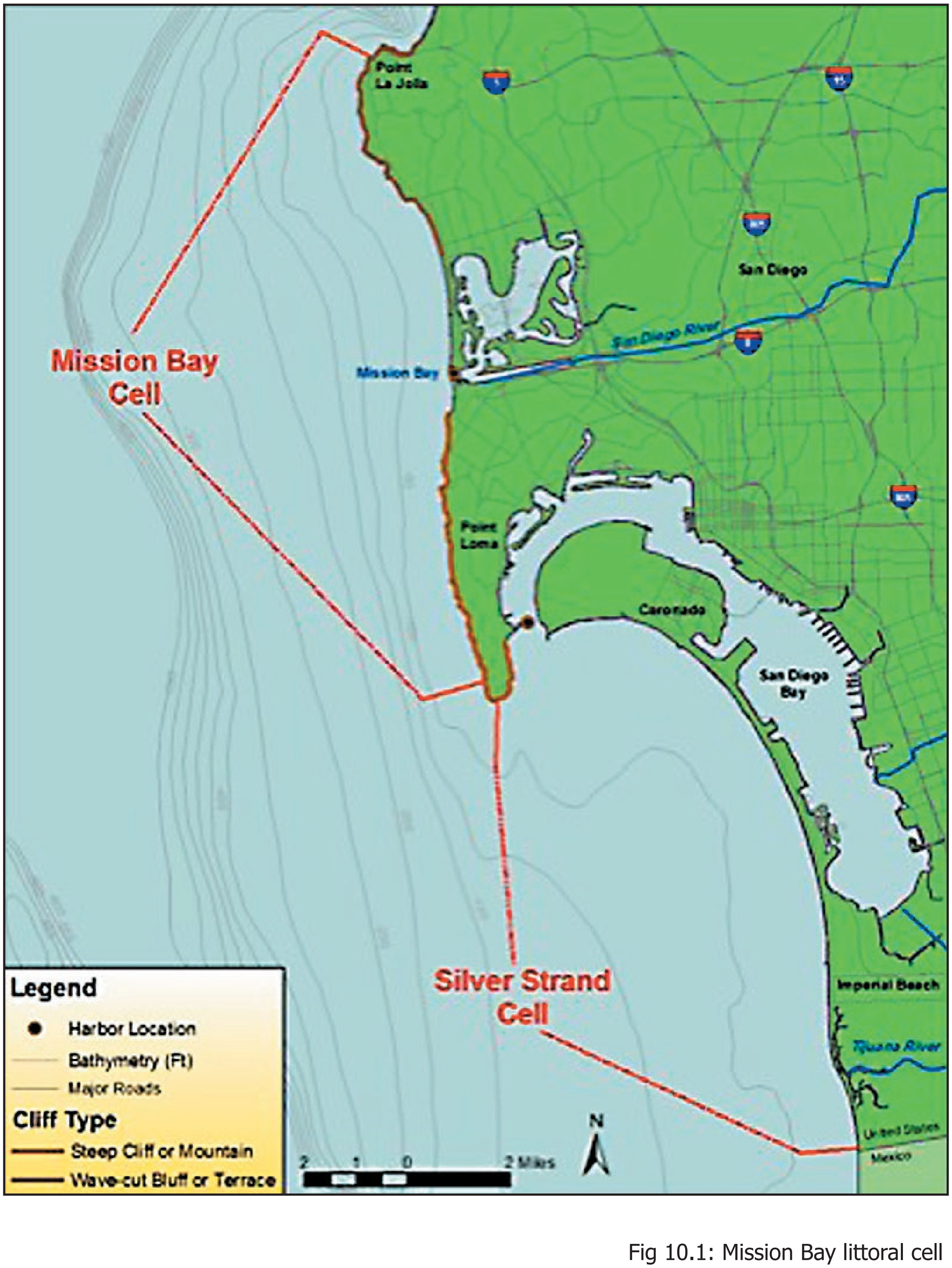

Fig 10.1: Mission Bay littoral cell

Fig 10.2: False Point showing the rocky shoreline of Point La Jolla Copyright © 2002 Kenneth & Gabrielle Adelman

Point La Jolla is a large, Cretaceous-age, rocky promontory distinguished by narrow pocket beaches, caves, and uplifted, wave-cut terraces. Extensive development exists near the cliff edge on this headland; shoreline armoring has been emplaced to protect private, cliff-top development (Figure 10.2).

Located just south of Point La Jolla, Pacific Beach, a moderately wide, sandy beach, extends for 1.5 miles (Figures 10.3 and 10.4). This beach is backed by cliffs or bluffs and dunes ranging in height from ~60 feet at the northern end to beach level at the southern end. The back beach along this reach of coast is extensively developed with residential properties in the northern stretch and commercial development occupying the southern portion. Despite the extensive development fronting Pacific Beach, there are few shoreline protection structures along the northern part of this area; south of Crystal Pier, however, a low concrete seawall is nearly continuous along the back beach (Figure 10.4).

MISSION AND OCEAN BEACHES

Located adjacent to Pacific Beach, Mission Beach is bordered on its west side by the Pacific Ocean and on its east side by Mission Bay (Figures 10.3 and 10.5). Wide, sandy beaches exist on the ocean side; narrow to moderately wide beaches exist on the bay side. These beaches are intensively used recreational areas due to excellent access (access exists at the end of nearly every street) and their proximity to San Diego. Mission Beach has been extensively developed, primarily with residential homes.

Fig 10.3: Mission Bay Littoral Cell (below)

Mission Beach is low-lying and prone to flooding. Beaches on the west, or ocean, side also have coastal hazards associated with wave attack and beach erosion.

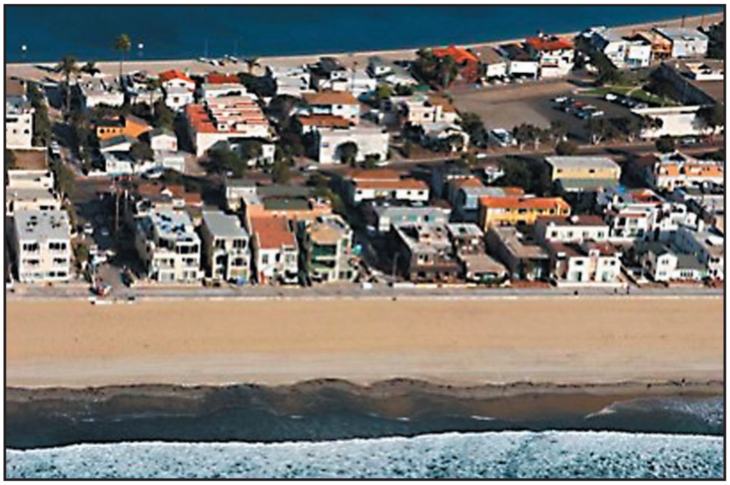

Fig 10.4: Southern End of Pacific Beach, San Diego Copyright © 2002 Kenneth & Gabrielle Adelmanassociated with wave attack and beach erosion.

The northern jetty stabilizing the entrance to Mission Bay interrupts littoral drift traveling south, trapping sand and creating a wide, sandy beach at the southern end of Mission Beach. Mission Beach is backed by a concrete seawall and promenade, which were overtopped and damaged by large waves during the El Niño winters of 1982-82 and 1997-98 (Griggs et al., 2005). Both Pacific and Mission beaches rest on the former delta of the San Diego River (Griggs et al., 2005).

Fig 10.5: Mission Beach, San Diego Copyright © 2002 Kenneth & Gabrielle Adelman

Mission Bay, formerly called False Bay, is an extensively modified wetland where development began as early as 1921 for boating and tourist activities. Mission Bay is now the largest aquatic park in the world, generating significant revenue for the city of San Diego (Griggs et al., 2005).

In 1949-1950, three straight, parallel, rubble-mound jetties were constructed in a combined flood control project for the San Diego River and Mission Bay Aquatic Park (Figure 10.6). The north jetty, middle jetty, and south jetty are 3,300-feet-long, 3,800-feet-long (extended to 4,270 feet in 1970), and 1,500-feet-long (extended to 2,050 in 1970) respectively (Wiegel, 1994). The middle and south jetties create the 800-foot-wide San Diego Flood Control Channel (Figures 10.6 and 10.7).

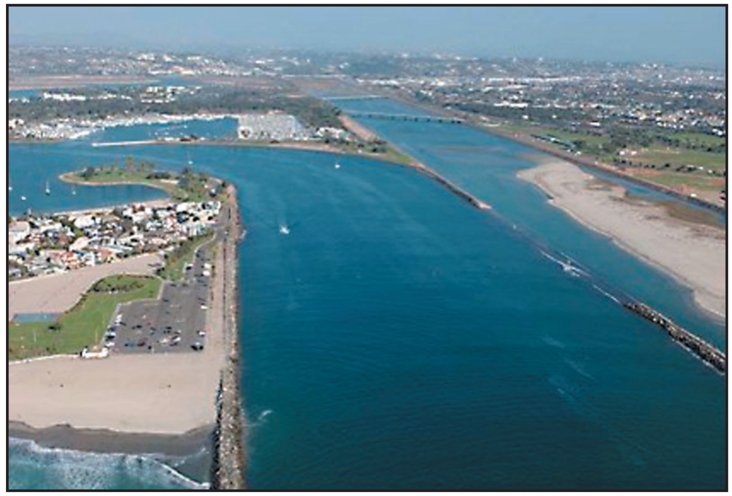

Fig 10.6: Entrance to Mission Bay on the left; San Diego River channel on the right. Copyright © 2002 Kenneth & Gabrielle Adelman

In 1950, a channel was dredged through the north and middle jetties, which are 919 feet apart crest to crest, to create an entrance into Mission Bay; however, the channel was not dredged deep enough, and by 1951 the channel was essentially closed (Hales, 1979). The Korean War interrupted further work on this project until 1955. In 1975, the channel was dredged to a depth of -20ft MLLW meeting standard navigational requirements (Hales, 1979; Herron, 1972; Wiegel, 1994).

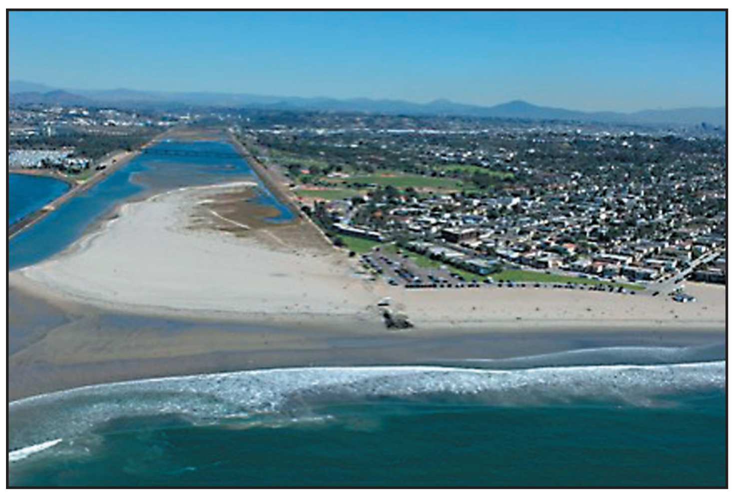

Fig 10.7: Mouth of the San Diego River, 2006. Copyright © 2002 Kenneth & Gabrielle Adelman

Maintenance dredging is required in the entrance channel to Mission Bay because of the small tidal prism relative to the navigational depths required and the width of the entrance channel (O'Brien, 1931; Wiegel, 1994). Since 1948, almost 2 million cubic yards (or 34,000 yd3/yr on average from 1948-2005) have been dredged from the entrance channel and placed on the beaches in the Mission Bay littoral cell, often backpassed upcoast to nourish Mission and Pacific beaches (Chang, 2001;

2005). Overall, including the interior of Mission Bay, 2.5 million cubic yards of sand (or 44,000 yd3/yr from 1948-2005) have been dredged from Mission Bay and placed on the adjacent beaches (Table 10.1).

Date	Quantity (yd^3/yr)	Disposal Location
1948*	600,000	Pacific Beach
1950	67,000	Ocean Beach
1955*	347,440	Unknown
1957/58	150,000	Mission Beach
1959	342,000	Ocean Beach
1973*	287,150	Pacific Beach
1983*	276,120	Unknown
1984*	448,000	Mission Beach & Ocean Beach
Total 2,517,710 Annual Average (1948-2005) 44,170 yd^3/yr		

Table 10.1: Dredging and Disposal History of Mission Bay.*Entrance Channel Dredging or Bypassing (~34,400 yd^3/yr: average annual maintenance dredging from entrance channel alone). Sources: (Chang, 2001; 2005; Griggs, 1987b; Wiegel, 1994)

Point Loma, much like Point La Jolla, is uplifted Cretaceous-aged bedrock (Figure 10.3). Ocean Beach, extending 0.6 miles (Figure 10.8), is the only long sandy beach on Point Loma.

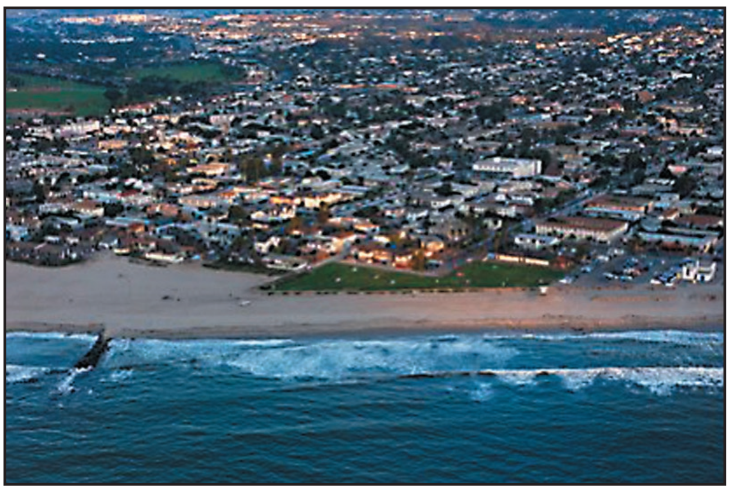

Fig 10.8: Ocean Beach, Mission Bay Littoral Cell. Copyright © 2002 Kenneth & Gabrielle Adelman

The majority of the beaches along this point are pocket beaches located between rocky headlands with poor access, with the exception of excellent coastal access at the southern end through Cabrillo National Monument. The steep cliffs along much of Point Loma are up to 300-feet-high and susceptible to wave attach and erosion (Figure 10.9).

The ocean edge of Point Loma is home to the residential and commercial communities of Ocean Beach and Sunset Cliffs (Figures 10.8 and 10.9), in addition to naval facilities and the San Diego regional sewage treatment plant. Ocean Beach and Sunset Cliffs are erosion hotspots and problem areas. In the summer of 1955, a rock groin was constructed to retain ~275,000 yd^3 of sand dredged from Mission Bay and placed on the Ocean Beach. Bluff retreat at Sunset Cliffs has damaged public streets and destroyed public and private land.

Fig 10.9: Sunset Cliffs, Point Loma; collapsed cave and crenulated shoreline Copyright © 2002 Kenneth & Gabrielle Adelman

Erosion of these cliffs is due to wave-induced erosion at the base of the cliffs in addition to bluff-top erosion from surface run-off and human activities. Various types of shore protection structures have been built over the years in an attempt to mitigate the erosion and protect the development. An investigation by the Army Corps of Engineers found that coastal bluffs at Sunset Cliffs retreated 40 feet between 1962 and 1976 (a long-term average erosion rate of almost 3 feet per year) at the end of Del Mar Ave (Figure 10.10) (Griggs et al., 2005).

Fig 10.10: Shoreline armoring at the end of Del Mar Ave, Point Loma. Copyright © 2002 Kenneth & Gabrielle Adelman

SAND SOURCES

Rivers: Mission Bay was originally one of two natural outlets of the San Diego River, the other being San Diego Bay. In 1855, the U.S. Army Corps of Engineers constructed a levee to divert the San Diego River to permanently discharge into Mission Bay (then called False

Bay)(Herron, 1986; Wiegel, 1994). This levee had to be rebuilt in 1875 and again in 1885 after it was washed out by flooding (Wiegel, 1994). The mouth of the San Diego River is often closed by littoral drift during extreme rainfall and run-off events creating flooding concerns for Mission Valley (sediment accumulation at the mouth of the San Diego River can be seen in Figure 10.7). A lowered weir was constructed into the middle jetty allowing for potential floodwaters to discharge through both the river channel and the entrance to the bay (Griggs et al., 2005).

The San Diego River is a source of sand to the Mission Bay littoral cell. This river drains an area of ~435 square miles, 88% of which is mountainous. For most of the year, the lower reaches of this river are essentially dry due to the construction of two large reservoirs; during the summers, the headwaters are also dry (Hales, 1979). The rock-lined, San Diego Floodway prevents discharge from entering Mission Bay.

Dams built on the San Diego River have reduced the sand supply to the shore by ~91% (Willis et al., 2002). Historically, the San Diego River contributed 71,900 yd^3/yr of sand, on average, representing 43% of the sand in the overall littoral budget for this littoral cell. Dams have reduced this yield to 6,600 yd^3/yr of sand (Willis et al., 2002), representing only 7% of the littoral budget for the Mission Bay littoral cell (Table 10.2).

Mission Bay Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers Bluff Erosion Beach Nourishment	71,900 (43%) 93,700 (5%) 0 (0%)	6,600 (7%) 77,000 (82%) 10,500 (11%)	65,300 (91%) 16,700 (18%) +10,500 (0%)
Total Littoral Input	165,600 (100%)	94,000 (100%)	71,500 (57%)

Table 10.2: Overall sand contributions and reductions to the Mission Bay littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment. Nourishment includes sand dredged from the interior of Mission Bay but not entrance channel dredging (which is considered bypassing).

Cliffs: Over 9.5 miles of this shoreline are backed by cliffs or bluffs ranging in height from 10- to 300-feet with capping terrace deposits up to 20-feet-thick. Erosion rates for these cliffs range from 1 to 3 feet per year. The bedrock is comprised of 39.5% beach-sand-sized sediment (coarser than 3.25Ø or 0.105 mm, the littoral cut-off diameter in this cell) while the terraces are composed of 88% beach-sand-sized sediment. Armor fronts 2.3 miles of the cliffs and bluffs, essentially removing, for the purposes of this study, the bluffs protected by the armor as a sand source. Seacliff erosion naturally provided an average of ~93,700 yd^3/yr of beach-compatible sand to this cell, representing 57% of the overall natural littoral budget. Seacliff armoring has reduced this volume by 18% to ~77,000 yd^3 of sand annually (Table 10.2). The majority of this sand (70,000 yd^3/yr naturally and 63,000 yd^3/yr after armoring) is derived from the 4.5 mile stretch of coast from Sunset Cliffs to the southern end of Point Loma.

Beach Nourishment: As stated earlier, about 2.5 million cubic yards of sand (or 44,170 yd^3/yr from 1948-2005) have been dredged from Mission Bay and from the entrance channel and placed on either upcoast or downcoast beaches. However, almost 2 million cubic yards of this total (or 34,400 yd^3/yr from 1948-2005) have been dredged from the entrance channel (Chang, 2001) and is, therefore, considered bypassing or backpassing rather than nourishment. The difference between these two, about 500,000 yds^3, or 9,000 yd^3/yr, 10% of the present-day littoral budget, came from Mission Bay and is included as nourishment in the budget (Table 10.2). As part of the 2001 SANDAG nourishment project, 100,000 yds^3 of additional sand was placed on Mission Beach. This has been added to the nourishment component of the budget (Table 10.2)

SAND SINKS

There are no submarine canyons reaching into the nearshore zone in the Mission Bay littoral cell. The largest sand sink is assumed to be offshore as littoral drift travels south along Point Loma and is lost around its tip. Offshore losses have not been quantified for this littoral cell by previous researchers, and therefore, have not been calculated in this study. In order to balance the littoral cell budget, a long-term average of ~83,000 yd^3/yr of sand are assumed to be lost offshore or stored behind retention structures in the reach of shoreline from Mission Bay to Point Loma, and an average of 12,000 yd^3/yr in the stretch of coast from Point La Jolla to Mission Bay.

Littoral Drift: Net littoral drift in this cell is minimally to the south in the Mission Bay littoral cell. Wave exposure is reduced by the sheltering effects of the offshore islands of San Clemente, Santa Catalina, San Nicholas, Santa Cruz, Santa Rosa, and the Los Coronados Islands of Mexico. In addition, submerged shoals south of San Clemente Island, Tanner Banks and Cortez Banks, also reduce wave exposure providing sheltering to the shoreline. Thus, the shoreline in this cell is exposed to varying wave energies related to the shoreline configuration and the location of offshore islands creating wave exposure windows in some locations and sheltering in others (Hales, 1979). Southward directed transport appears to be only slightly greater than the northward transport, resulting in minimal net southward movement of sand.

SUMMARY

The sand budget for the Mission Bay littoral cell is shown in Figures 10.11 and 10.12 (found on the following 2 pages) as a box model and a running, cumulative, mile-by-mile budget respectively. From Point Loma to Mission Bay, sand is added to the system through seacliff or bluff erosion (~9,000 yd^3/yr), and beach nourishment from dredging in the interior of Mission Bay (~3,000 yd^3/yr). The entrance channel to Mission Bay is dredged periodically (averaging ~34,000 yd^3/yr), which is back-passed upcoast to nourish Pacific Beach and Mission Beach. Adjacent to Mission Bay, on the downdrift or southern side of the entrance channel, the San Diego River discharges an average of ~6,600 yd^3 of sand annually. Ocean Beach is nourished with sand periodically dredged from the interior of Mission Bay (~7,000 yd^3/yr). The largest sand source is the erosion of seacliffs along the shoreline of Point Loma, which adds an average of ~69,000 yd^3/yr of sand to the littoral budget. The surplus of sand in the southern portion of the cell (~83,000 yd^3/yr) is assumed to travel south along Point Loma and is then lost offshore, or stored in pocket beaches between Ocean Beach and the end of Point Loma.

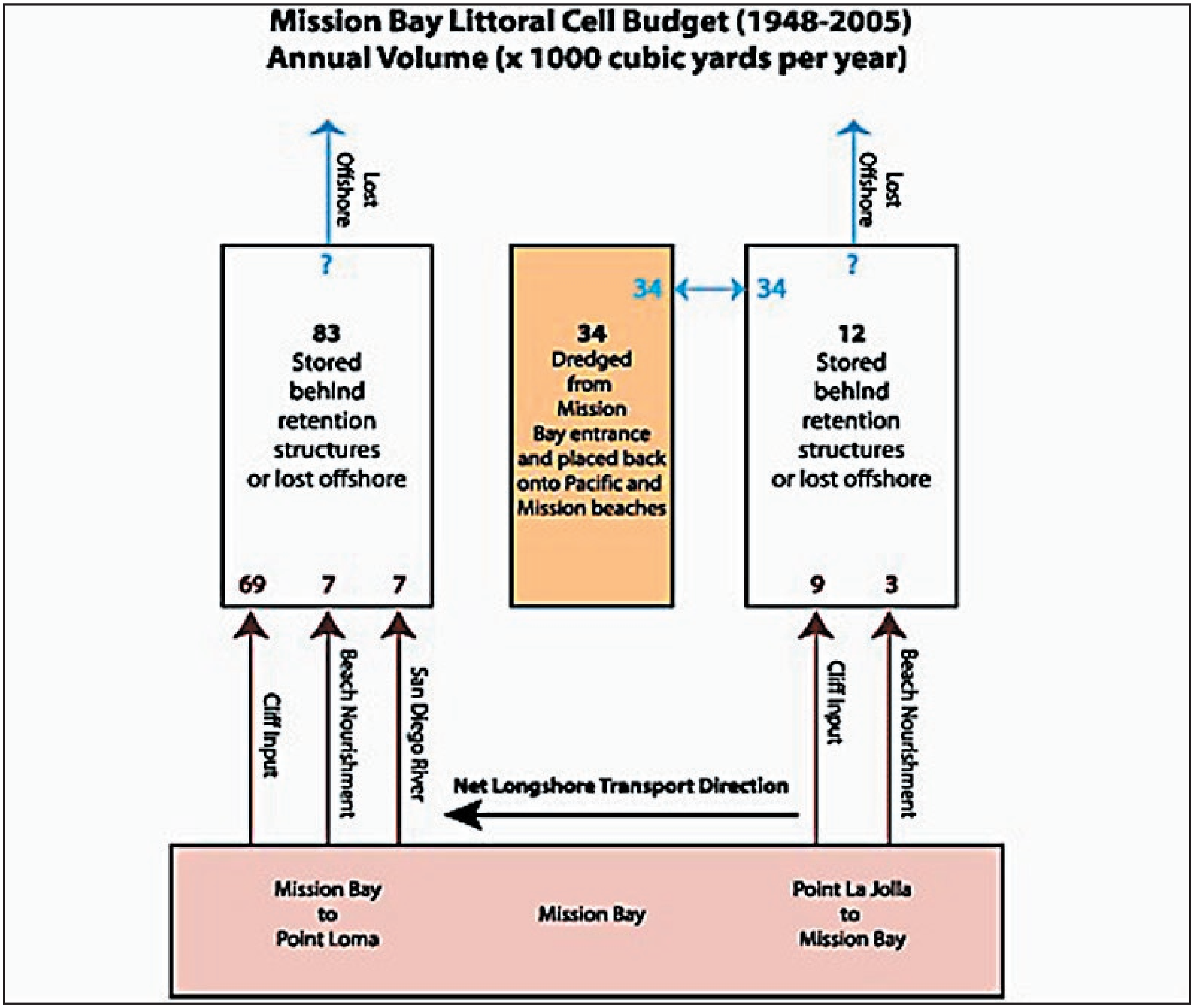

Fig 10.11: Mission Bay Sand Budget (1948-2005)

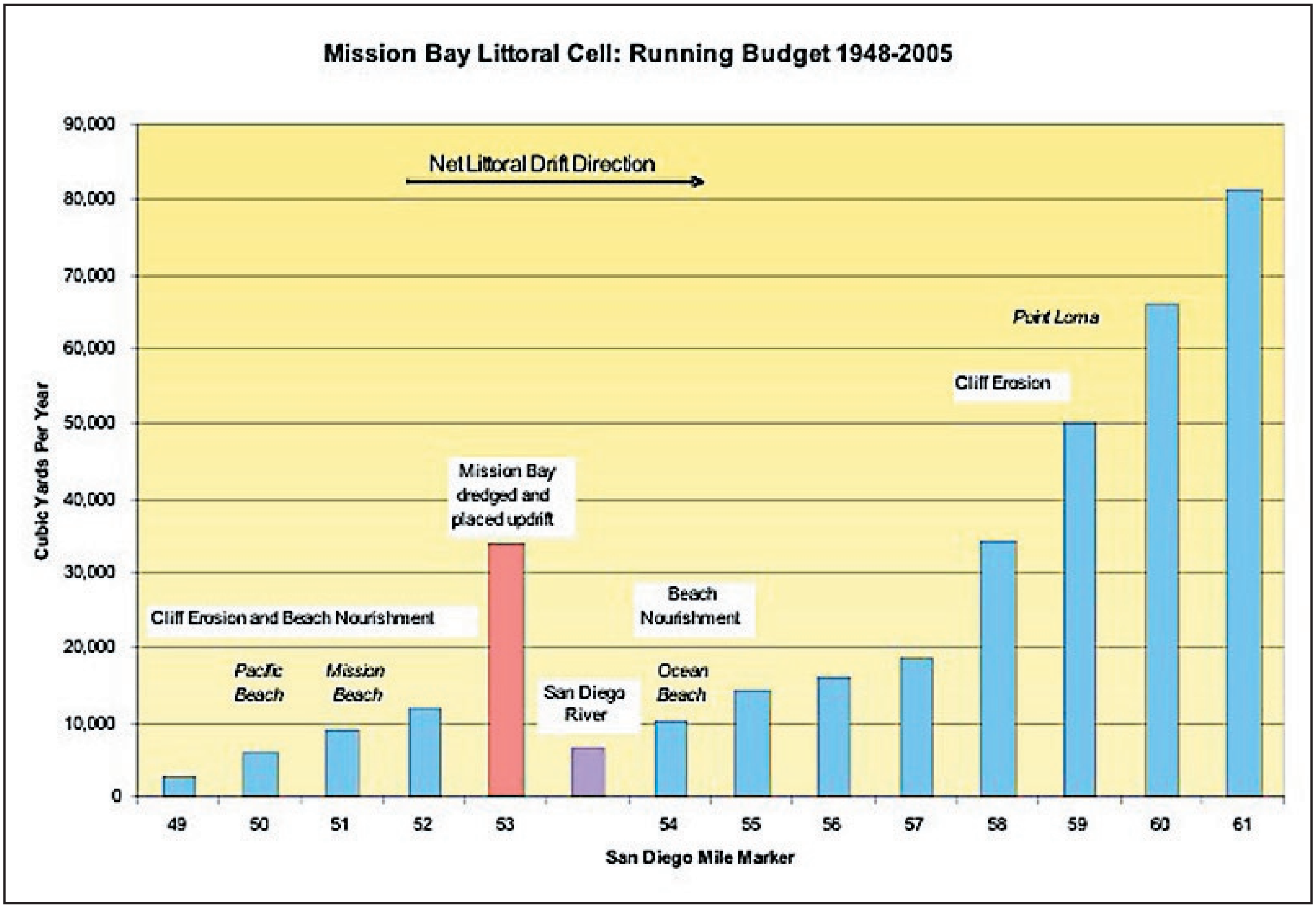

Fig 10.12: Running Budget for the Mission Bay Littoral Cell

CHAPTER 11

SILVER STRAND LITTORAL CELL SAND BUDGET

Silver Strand littoral cell (Figure 11.1) extends from the entrance of San Diego Bay south past the international border (Figure 11.2) and into Mexico, encompassing 16 miles of shoreline in California and another 20 miles into Mexico to Punta El Descanse (Wiegel, 1994). Wide, sandy beaches occupy the shoreline in the California portion of this cell, which will be the focus of this sand budget. South of the Tijuana River delta, the shoreline consists of narrow, sandy beaches backed by bluffs. Beaches in this cell are the most highly altered in southern California.

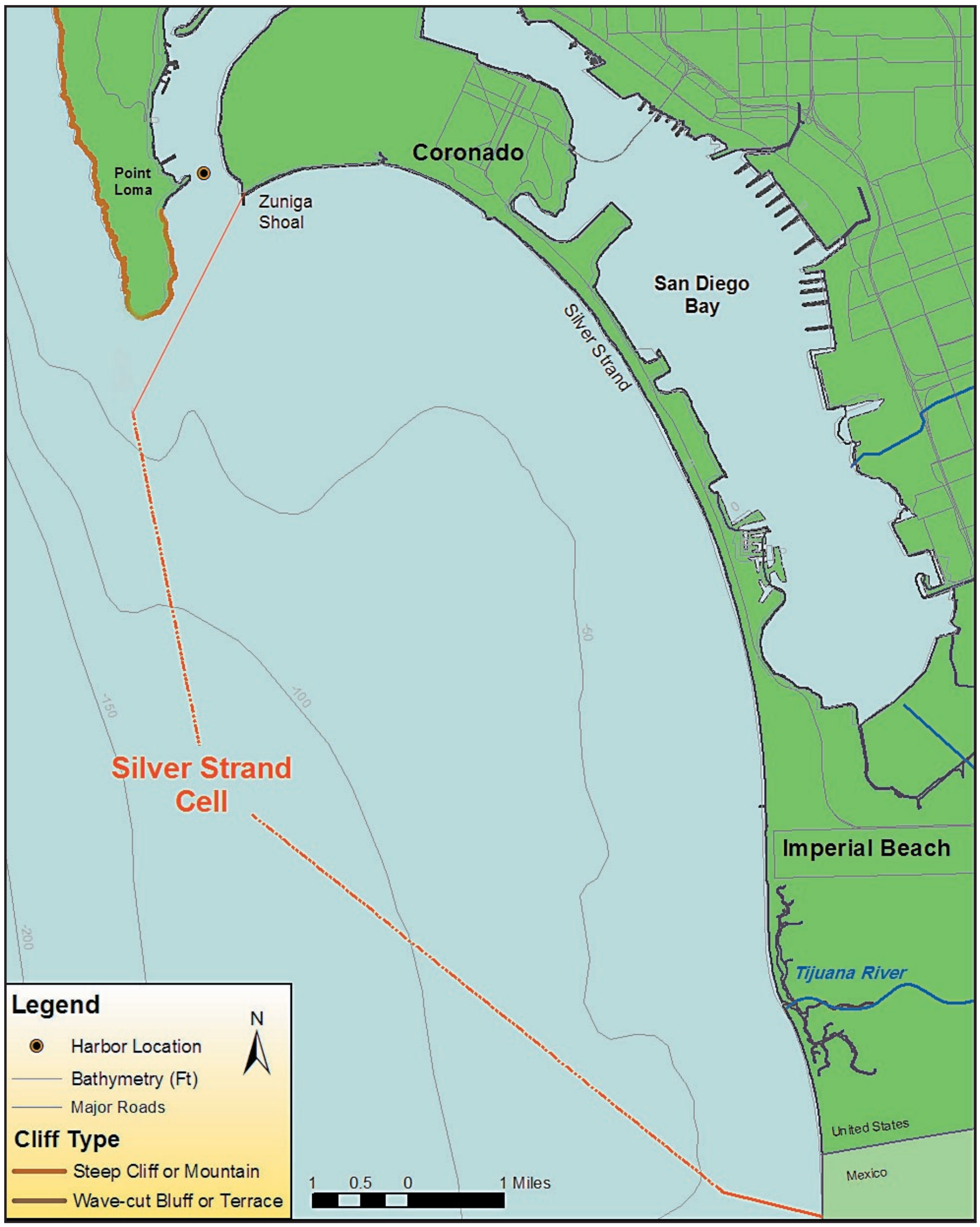

Fig 11.1: Location Map for the Silver Strand littoral cell

From 1940 to 2005, beach nourishment projects added almost 40 million yds^3 of sand to this cell in an attempt to mitigate severe beach erosion at Imperial Beach, Silver Strand Park and in the past, Coronado (Flick, 1993; Inman, 1973; Inman, 1974; Inman, 1976; Wiegel, 1994).

San Diego Bay or Harbor is an 18-mile-long, elongated, crescent shaped embayment with a variable width and a high tide area of 16.6 square miles. The Bay is separated from the Pacific Ocean by a narrow sand barrier, Silver Strand, which is connected to Coronado Island and North Island. The entrance to San Diego Bay is self-scouring to a depth of 25 feet; however it is dredged to ~45 ft by the Army Corps of Engineers.

San Diego Bay is a major naval, commercial, and recreational center at the extreme southern limit of California's coast, approximately 110 miles south of Los Angeles. The Navy has facilities at the inner, northern end of the harbor approximately seven miles from the entrance channel. This harbor is a major stopping point for agricultural goods from southern California, Arizona, and New Mexico, and is also the center of the west coast commercial tuna fishing industry. Recreational facilities are near the north end of the harbor and along the shore of Silver Strand.

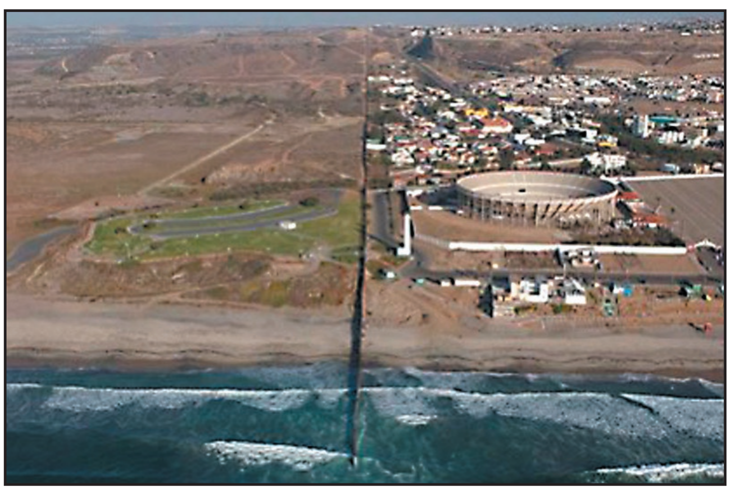

Fig 11.2: International Border: United States on the left; Mexico on the right. Copyright © 2002 Kenneth & Gabrielle Adelman

Pt. Loma is considered the northern boundary of the Silver Strand Cell (Habel and Armstrong, 1977). The 7,500-foot-long, rubble-mound Zuniga Jetty, completed in 1904, located on the east side of the entrance to San Diego Bay, forms a littoral barrier for littoral transport moving north along the Silver Strand (Figure 11.3). Around 1900, a 1,400-foot-long curved groin was constructed adjacent to the Hotel del Coronado (Figure 11.4) to provide safe anchorage to boats.

The 3-mile-long stretch of coast between Zuniga Jetty and this groin is likely the widest beach in southern California (Flick, 1993). This beach remains relatively stable because it is located at the downdrift end of the littoral cell; it is protected from all waves except those from due south, and is essentially trapped between two shore-normal structures (Flick, 1993).

Fig 11.3. Zuniga jetty at the eastern side of the entrance to San Diego Bay. Copyright © 2002 Kenneth & Gabrielle Adelman

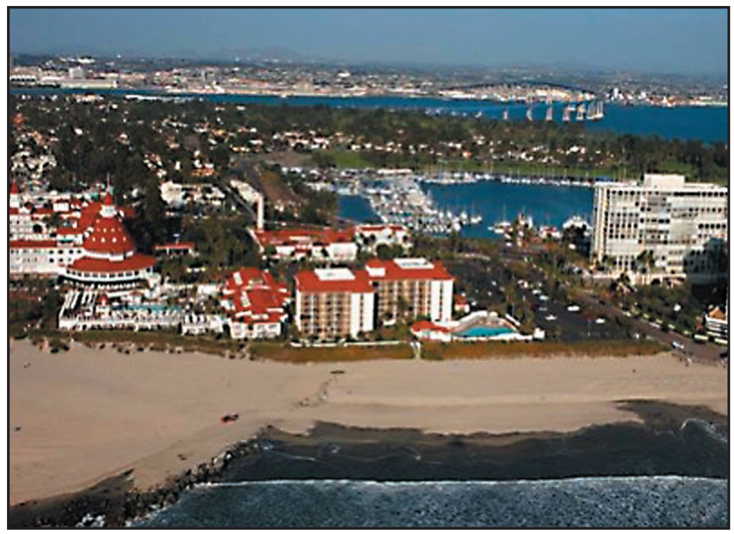

Fig 11.4: Hotel del Coronado, Coronado, California showing groin. Copyright © 2002 Kenneth & Gabrielle Adelman

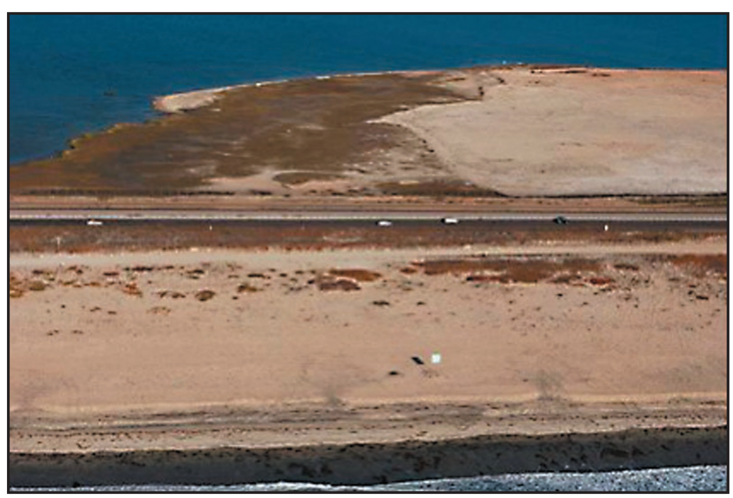

Fig 11.5: Silver Strand State Beach, California: Silver Strand Littoral Cell Copyright © 2002 Kenneth & Gabrielle Adelman

Silver Strand (Figure 11.5) is a relatively narrow stretch of beach separating San Diego Bay from the Pacific Ocean attached at the northern end to Coronado Island. Coronado (Figure 11.6) is a flat low-lying island, which was originally two distinct landmasses separated by Spanish Bight, a reentrant of San Diego Bay. In 1944, artificial fill was placed in Spanish Bight connecting the northernmost island, North Island, to Coronado.

The continental shelf seaward of Silver Strand extends 15 miles offshore, gently sloping seaward to a depth of 600 feet at the shelf edge. Tijuana Estuary (Figure 11.7) is located at the southern-most part of the California reach of the Silver Strand littoral cell near the mouth of the Tijuana River. The northern side of the lagoon is bounded by a gently sloping marine terrace ranging in height from 50- to 100-feet above sea level, which separates San Diego Bay from the Tijuana River Valley. This elevated marine terrace is occupied by the community of Imperial Beach (Figure 11.8).

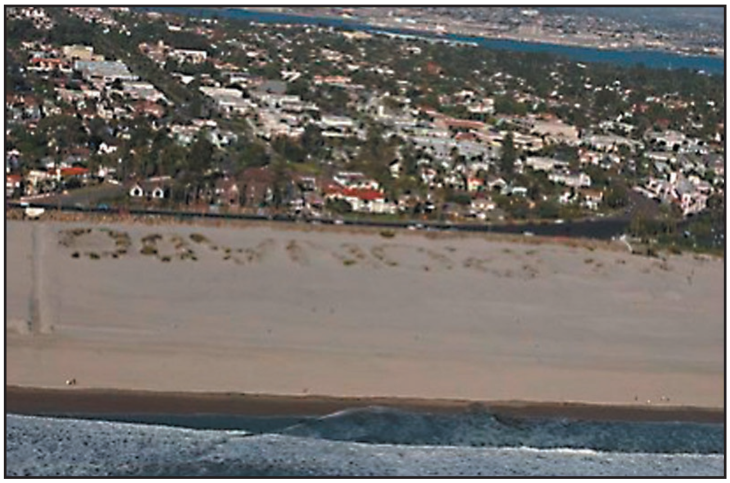

Fig 11.6: Coronado, California: Silver Strand Littoral Cell Copyright © 2002 Kenneth & Gabrielle Adelman

Fig 11.7. Tijuana River Estuary at the mouth of the Tiajuana River. Copyright © 2002 Kenneth & Gabrielle Adelman

Man's alterations to the coastline have significantly changed the beaches in this cell resulting in persistent beach erosion at specific locations. Beach erosion has been documented at the southern end of Imperial Beach since 1937. In the 1950's, problems resulting from beach erosion extended to the northern end of Imperial Beach. As a result, the Army Corps of Engineers was authorized by the River and Harbors Act of 1958 to construct five rock groins along the City of Imperial Beach shoreline in an attempt to stabilize and maintain the beach for recreational purposes and to prevent over-wash into backshore areas.

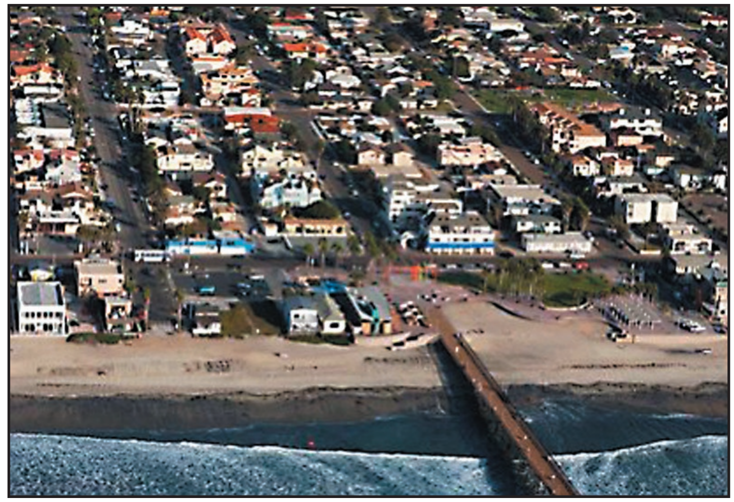

Fig 11.8: Imperial Beach and Imperial Beach Pier. Copyright © 2002 Kenneth & Gabrielle Adelman

The plan called for five groins to be placed along the shoreline at intervals of 1,000 feet. The first groin was constructed in 1959 at the northern end of the city and was lengthened in 1963. This groin proved ineffective at trapping sand, so the second rock groin was built just south of the first one in 1961. Both of these structures were ineffective at controlling beach erosion due to the lack of sand traveling as littoral drift at this location, and the project was subsequently abandoned (Inman, 1976).

In 2002, the Army Corps of Engineers reactivated the City of Imperial Beach project and began investigating alternative means to stabilize and restore the beach. According to estimates made by the Corps of Engineers (2002), ~100,000 yd^3/yr of sand is eroding from the shoreline of Imperial Beach, corresponding to a retreat rate of 6.6 feet per year. Occasional beach nourishment projects have slowed the retreat; however, the projects have not been large enough in scale, or placed enough sand, to halt the erosion. At the current retreat rate, the shoreline in the northern portion of Imperial Beach could reach the first line of development by 2007 (USACOE, 2002). As part of the 2001 SANDAG nourishment project, 120,000 yds^3 was added to Imperial Beach. The Army Corps of Engineers has plans to nourish the nearshore region with an additional 650,000 cubic yards of sand to mitigate erosion (Ryan, 2005).

LONGSHORE TRANSPORT

There is a pronounced shoal offshore of Imperial Beach and the Tijuana Estuary. Waves converge on this shoal resulting in an interruption of the longshore current. At this location, the longshore current diverges and flows northward and southward (Inman, 1974; Inman, 1976). Net littoral drift is to the north (north of the Tijuana River) in the Silver Strand littoral cell due to the sheltering effects of Point Loma from waves approaching from the north (Everts, 1987; Flick, 1993; Wiegel, 1994). There is a progressive decrease in mean grain size and better sorting north of the Tijuana River along Silver Strand, also supporting a net northward transport direction (Inman, 1973; Inman, 1974; Inman, 1976).

WAVE CLIMATE

The dominant source of wave energy to the Silver Strand littoral cell is northern hemisphere swell with periods of 6- to 10-seconds arriving from between 295° and 315°. Swell generated in the southern hemisphere is generally lower in height (~3 feet) and occurs predominantly in the summer. The shoreline of the Silver Strand littoral cell is sheltered by Point Loma, and offshore islands, including San Clemente, San Nicolas and Santa Catalina, which diffuse and obscure wave energy approaching from directions greater than 280° (Inman, 1976). The Los Coronados Islands, three islands located ~7 miles offshore just south of the International Border, shelter the shoreline to a lesser degree from southern swells.

SAND SOURCES

Rivers: Since the diversion of San Diego River in 1855 to Mission Bay, Tijuana River (Figure 11.7), discharging near the international border, is the only significant, natural sand source for the Silver Strand littoral cell. Tijuana River is formed by the confluence of Cottonwood Creek, draining the northern third of the drainage basin, and Rio de Las Palmas, draining the southern two thirds of the drainage basin. The watershed, totaling 1,700 square miles, extends through both Mexico and California with elevations ranging from sea-level to 6,000 feet in the upper part of the drainage basin (Inman, 1974; Inman, 1976). Cottonwood Creek is obstructed by Morena Dam (impoundment began in 1911) and Barrett Dam (impoundment began in 1921). The flow of Rio de las Palmas is obstructed by Rodriguez Dam (impoundment began in 1936) just upstream from the city of Tijuana. These three dams impound discharge from over 1,200 square miles, or 70% of the sediment producing drainage basin, from the coast (California, 1969; Inman, 1974; Inman, 1976).

These three dams have reduced the sand supplied to the Silver Strand cell from the Tijuana River by 49%, from an annual average of ~83,000 yd^3/yr to ~42,000 yd^3/yr (Table 10.1) (Willis and Griggs, 2003; Willis et al., 2002). For this report, based on beach widths, it is assumed that half of this small sand discharge travels north and ultimately ends up offshore near Zuniga Jetty, while the other half is transported south into Mexico.

Sediment entering the ocean from the Tijuana River is mostly fine-grained sand, silt and clay. Much of the coarser material is deposited in the Tijuana Estuary at the mouth of the Tijuana River (Figure 11.7). The estuary is accumulating large residual cobbles and boulders (Inman, 1976). Silt- and clay-sized particles remain in suspension flowing into the ocean where they are distributed over a large area by local currents. This fine-grained sediment is carried offshore before it eventually settles out of suspension.

Other coastal streams north of the Tijuana River, such as Otay and Sweetwater rivers and several small creeks in the city of San Diego, may also contribute minor amounts of sand to this cell. However, the total drainage area of all these creeks and streams is less than 600 square miles, and they all discharge into the east side of San Diego Bay. In addition, most of these small drainages are dammed. Thus, these streams are assumed to provide an insignificant volume of sand to the overall littoral budget for the Silver Strand cell.

Seacliff Erosion: Sand is added to the littoral budget through bluff erosion in the Mexico portion of the cell (Everts, 1987). Access was not available to this stretch of coast, thus an estimation of sand entering the littoral system from these cliffs is unavailable.

Beach Nourishment: The Silver Strand littoral cell is the most highly altered cell in southern California in terms of beach nourishment. San Diego Bay (Figures 11.1 and 11.3) serves as a deep-draft natural harbor formed by Point Loma to the north and Silver Strand sand spit on the west. From 1940 to 1941, 2.3 million yds^3 of sediment dredged from San Diego Bay were placed on North Island (Inman, 1976). From 1941 to 1946, the massive expansion of the naval facilities provided approximately 26 million yds^3 of additional sand from the bay to Silver Strand (Inman, 1976). Before this nourishment project, Silver Strand was a narrow, marginal, sand spit between San Diego Bay and the Pacific Ocean, which was often over-washed by ocean waves. This nourishment project widened the beach by up to one thousand feet from Silver Strand State Beach to Zuniga Jetty (Flick, 1993; Inman, 1976). Since 1946, the shoreline has retreated as sand eroded from the beaches was transported northward. Just south of the Hotel del Coronado, the Naval Amphibious Base has occasionally imported modest amounts of sand for nourishment creating beaches wide enough for training purposes. Recently, sand dredged from the bay has been transported as far south as Imperial Beach and placed offshore past the surf-zone (Flick, 1993).

However, nourishment projects have significantly decreased in recent years. Since the 1960's, an annual average of only ~256,000 yd^3 of sand have been placed on the beaches from the dredging of San Diego Harbor representing 86% of the total littoral budget for the Silver Strand littoral cell (Table 11.1).

Silver Strand Littoral Cell			
Inputs	Natural (cy/yr)	Actual (cy/yr)	Reduction (cy/yr)
Rivers	83,000 (100%)	42,000 (14%)	-41,000 (49%)
Beach Nourishment		256,000 (86%)	+256,000
Total Littoral Input	83,000 (100%)	298,000 (100%)	+215,000 (+259%)

Table 11.1: Overall sand contributions and reductions to the Silver Strand littoral cell. Reductions are due to the damming of the Tijuana River. "Natural" sand yield refers to the estimated original volume of sand discharged by streams. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions taking into account reductions in sand supply from dams and additional sand added through beach nourishment.

From 1941 to 2005 a total of approximately ~39,800,000 yd^3 (613,000 yd^3/yr) of sand dredged from San Diego Harbor (Figure 11.3) have been used for beach nourishment in the Silver Strand littoral cell (Table 11.2). Because this sand has come primarily from deepening of the harbor rather than entrance channel dredging, it is considered as beach nourishment in the budget.

In 2001, 120,000 yd^3 of sand from the SANDAG project were placed on Imperial Beach, but this is a very small volume relative to the magnitude of historic nourishment.

Year	San Diego Harbor (yd3)
1941-1947	29,868,000
1967-1976	3,485,000
1978	5,880,000
1987	260,313
1988	130,000
1989	97,470
1996	118,563
Total (yd^3)	~39,840,000
Yearly Average (yd^3/yr)(1941-2005)	~613,000
Yearly Average (yd^3/yr)(1967-2005)	~256,000

Table 11.2: Dredging History of San Diego Bay

SAND SINKS

Most littoral cells in southern California have a submarine canyon extending into the nearshore zone at the downcoast end of the cell, which acts as the dominant sink for the cell (Inman, 1974; Inman and Chamberlain, 1960; Inman and Frautschy, 1966). However, in the Silver Strand littoral cell, there are no submarine canyons. Instead, sand accumulates at shallow depths on the shelf. Before the construction of Zuniga Jetty, sand accumulated at the end of the cell in Zuniga Shoals (Figure 11.1). A strong ebb tidal current from San Diego Bay transported sediment offshore where it was deposited at relatively shallow depths. This sand would eventually be returned to the shoreline by waves refracted around Point Loma, thus, creating a system in dynamic equilibrium capable of maintaining the beaches at Coronado and a narrower beach at Silver Strand (Chamberlain et al., 1958).

After the construction of Zuniga Jetty, however, the dynamic equilibrium of the Silver Strand cell was disrupted. Sand became impounded in the nearshore area on the east side of the jetty, widening the beach and extending it into the shoal area. Some sand enters San Diego Bay through the permeable jetty and around the tip of the jetty where it is carried seaward by ebb tidal currents (Inman, 1973; Inman, 1974; Inman, 1976). Zuniga Jetty constricts the tidal flow, increasing the velocity and competence of the ebb tidal current in the entrance channel, transporting sand seaward beyond the tip of Point Loma. Sediment flowing in this tidal current is now transported into deeper water where it is permanently lost from the littoral cell. Offshore losses of sand in the region of Zuniga Shoals and seaward of Zuniga Jetty are the main sink for sand in the Silver Strand littoral cell (Everts, 1987; Inman, 1973; Inman, 1974; Wiegel, 1994).

SUMMARY

The sand budget for the California portion of the Silver Strand littoral cell is presented in Figures 11.9 and 11.10 as a simple box model and as a running, mile-by-mile, cumulative budget, respectively. The only natural source of sand to this littoral cell is the Tijuana River, contributing an annual average of ~42,000 yd^3 of sand to the littoral system. For the purpose of this budget, it is assumed that sand from the Tijuana River is divided equally between the north and south littoral drift that diverges at this location. Thus, 21,000 yd^3/yr of sand is shown to travel south into the Mexico portion of the littoral cell while the remaining 21,000 yd^3/yr travels north along Imperial Beach and the Silver Strand where it is eventually deposited into Zuniga Shoals, lost offshore, or accumulated in the entrance channel of San Diego Bay. Very large volumes of artificial fill from the dredging of San Diego Bay were historically added to the beaches of Silver Strand, Coronado and Imperial Beach totaling approximately 256,000 yd^3/yr.

With a decrease in beach nourishment projects and a reduction in the volume of sand provided by the Tijuana River, the sand budget for the Silver Strand has had a deficit in recent years. Although 120,000 yds3 were added as part of the SANDAG nourishment project, this was a very small volume of sand relative to historical nourishment from San Diego Bay dredging. The existing beach sand is now feeding the wave induced longshore transport causing beach erosion problems in many areas of the Silver Strand Cell. Net beach erosion, or retreat, has been shown to occur from Playas de Tijuana through Imperial Beach, on Silver Strand State Beach, and from South Coronado to the Hotel del Coronado (Everts, 1987; Flick, 1993).

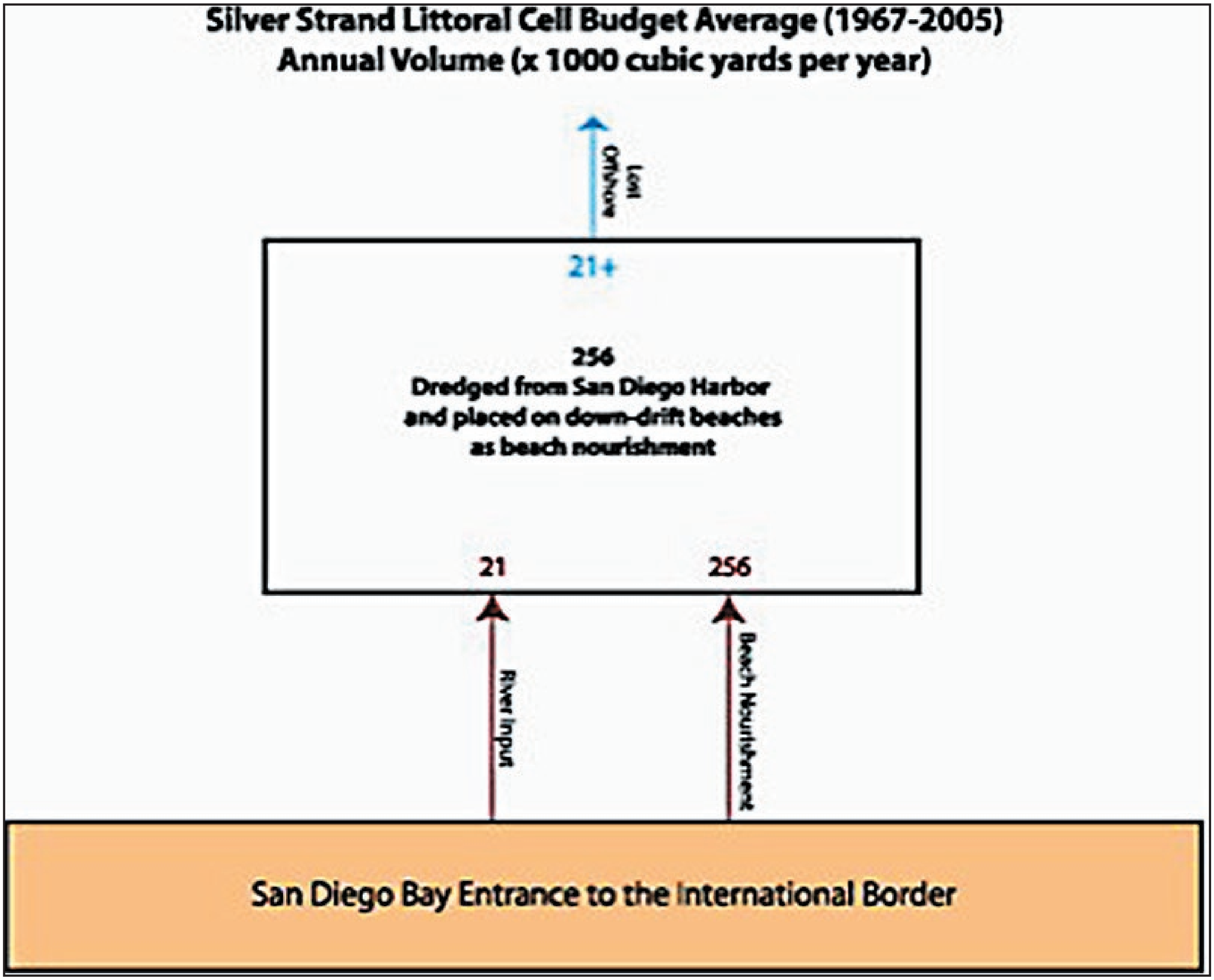

Fig 10.9: Sand Budget for the California portion of the Silver Strand Littoral Cell

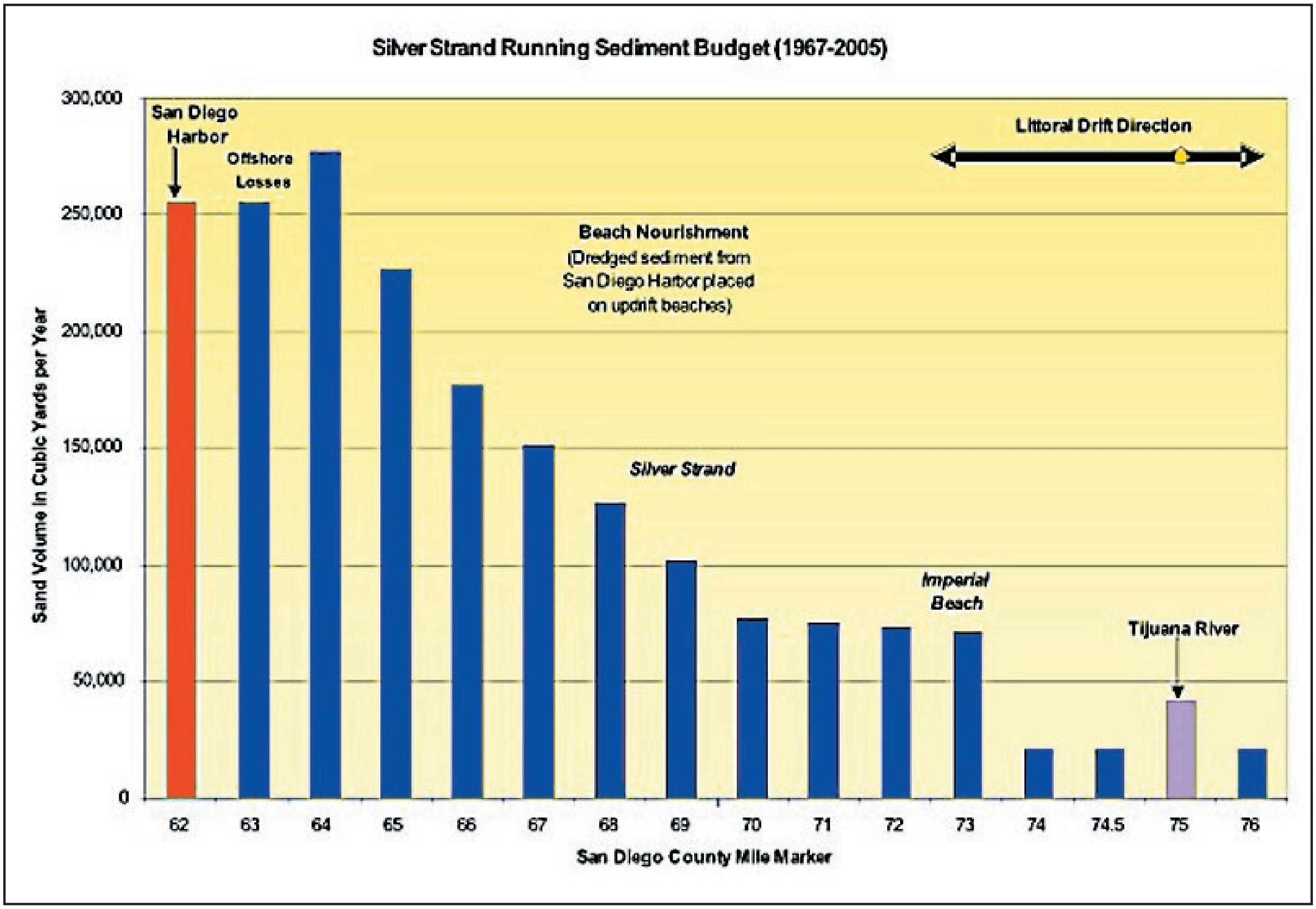

Fig 10.10: Running, mile-by-mile sand budget for the California portion of the Silver Strand Littoral Cell (1967-2005)

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