BEACHES, LITTORAL DRIFT AND LITTORAL CELLS

UNDERSTANDING CALIFORNIA'S SHORELINE

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Chapter 1: Introduction

People have been interested in beaches and coastal processes for many years. Researchers have observed that the beaches change significantly over a range of time periods, from hours and days to years and decades. In an effort to better understand the changes that take place and change beaches, scientists have developed the concept of a sediment budget that attempts to identify and quantify all the additions and losses of sediment that influence a particular segment of coast. In this process, it became clear to researchers by the 1960's that the coastline of California could be separated into distinct essentially self-contained regions or cells that were geographic limited. For example, that beach sand in the Santa Barbara area originated from the watersheds and the coastline in the Santa Barbara area and that there were different sources for the beach sand in San Diego or Santa Cruz.

Coastal geologists and engineers termed these self-contained coastal units littoral cells. These cells are geographically bounded by specific physical features

along the coastline that act as barriers to sediment exchange and allow researchers to focus on the main elements that influence specific beach or shoreline areas.

This paper discusses the physical elements that establish the boundaries of California's littoral cells, the features within the cell that supply sediment to the beaches (sediment sources), the features that remove sediment from the beaches (sediment sinks) and the mechanisms that move sediment within the cell (longshore transport or littoral drift). Information is also provided on how sediment budgets are developed for littoral cells, on the sources and sinks for the major littoral cells along the open ocean coast of California, and finally information is provided on how human development along the coast has altered the sediment budgets of many of California's littoral cells.

A more detailed report on specific sand budgets for all of California's major littoral cells has been completed and is a complement to this more general discussion (Patsch and Griggs, 2005).

Chapter 2: An Overview of Littoral Cells and Littoral Drift

What is Littoral Drift?

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. This current combined with the agitating action of the breaking waves, which serves to entrain the sand, are the essential factors creating sand movement 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 (Figure 2.1). This zigzag motion (waves washing onto shore at an angle and returning perpendicular or at a slight downcoast angle to the ocean) results in a longshore current parallel to the shoreline. Littoral drift refers to the movement of sand grains in the direction of the longshore current.

Littoral drift can be thought of as a river of sand moving parallel to the shore. Littoral drift or transport in California can occur alongshore in two directions, upcoast or downcoast, dependent on the dominant angle of wave approach (Figure 2.2; along the California coast we generally refer to southward transport as downcoast and northward transport as upcoast). If waves approach perpendicular to the shoreline (at a 90 degree angle), there will be no net longshore movement movement of sand grains and no littoral current, thus no littoral drift. Longshore transport for a reach of coast will typically include both

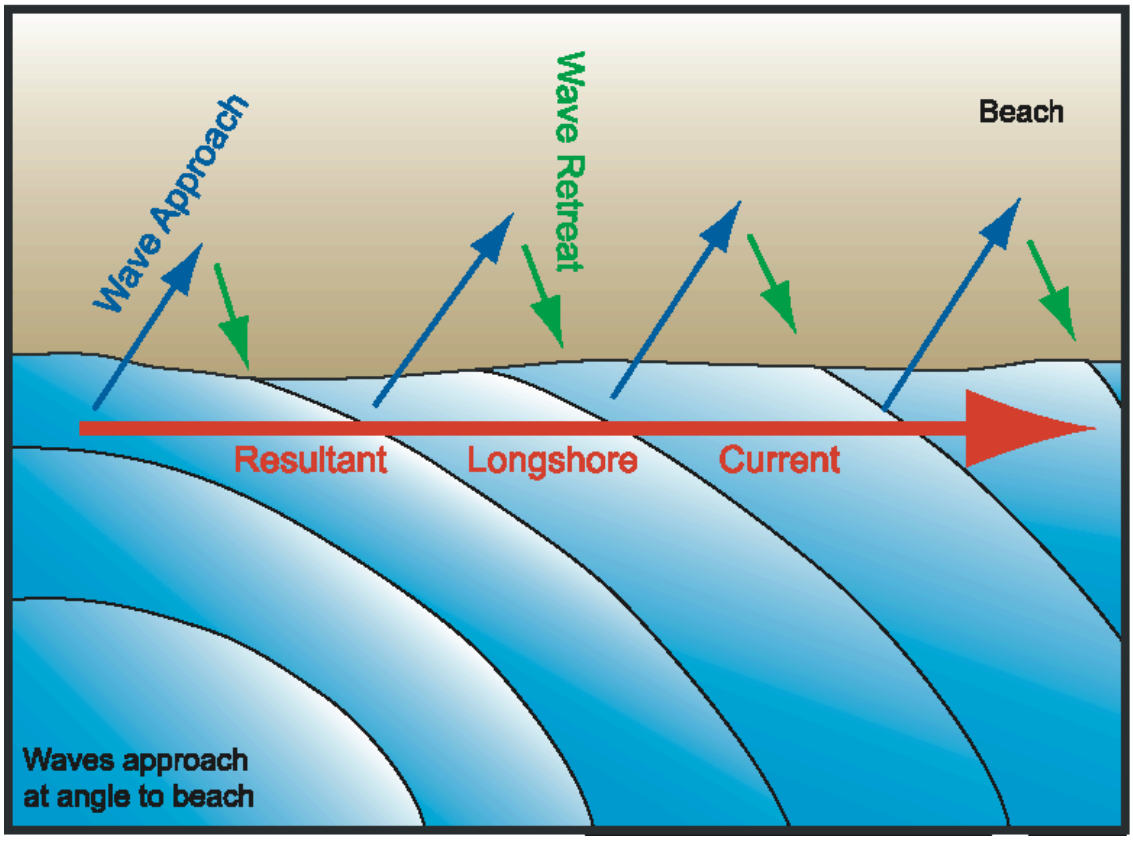

Figure 2.1: Development of a longshore current as a result of waves approaching the beach at an angle. Littoral drift refers to the net movement of sand grains in the direction of the longshore current.

upcoast and downcoast transport, often varying seasonally. Gross littoral drift is the drift is the total volume of sand transported both up and down coast, while net littoral drift is the difference between the two volumes. In other words, along a particular segment of coastline, there may be 200,000 yds^3 of sand transported in a southerly or downcoast direction each year, and 50,000 yds^3 transported in a northerly or upcoast direction. The gross littoral drift would be 200,000 + 50,000 or 250,000 yds^3, whereas the net drift would be 200,000 – 50,000 or 150,000 yds^3 downcoast.

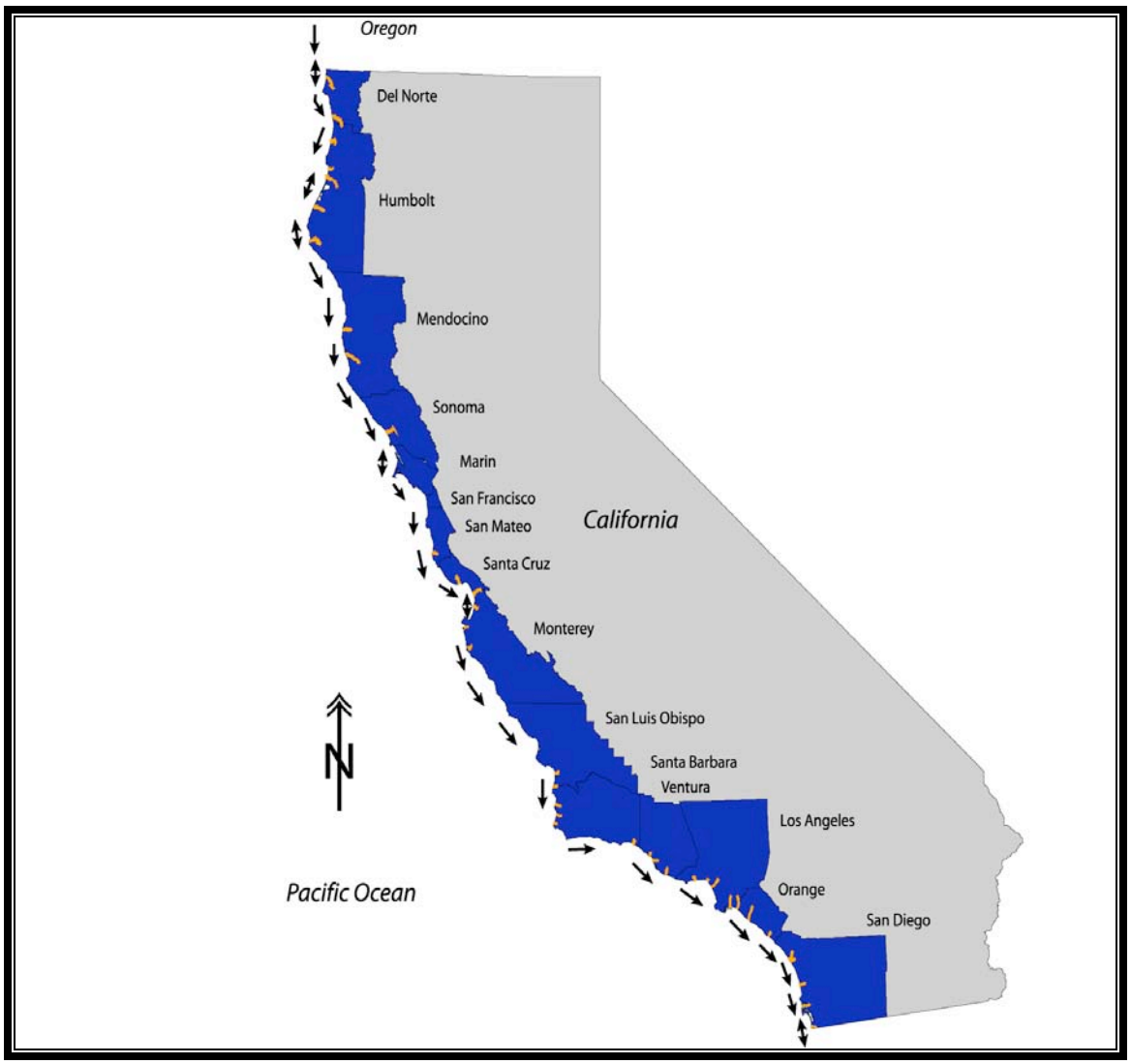

Figure 2.2: Net littoral drift directions in California

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 southward net littoral drift of sand dominates (Figure 2.2). The more energetic winter waves generally approach from the northwest direction, and drive littoral drift southward or southeast along the beaches. There are also areas such as southern Monterey Bay, and Oceanside, where longshore transport to the north

takes place. In addition, during El Niño winters waves generally come from the west or southwest and the southward transport is reduced. Transport is often to the northwest, or upcoast, in most of southern California during the summer months when southern swell dominates.

Coastal engineering structures designed to prevent beach erosion, such as groins, the construction of harbor entrance jetties and breakwaters, and also the stability or lifespan of beach nourishment projects, are all closely tied to littoral drift direction and rate. Littoral drift is essentially a river of sand running parallel the shore. Interrupting or disrupting this river of sand will have serious consequences to the downdrift shorelines including increased beach or cliff erosion and, in the case of a harbor entrance, costly dredging. Erosion of downdrift properties may necessitate the emplacement of additional coastal armoring, which extends the disruptions to the shoreline farther and farther downcoast.

What Constitutes Beach Sand?

Whereas it is common practice to refer to most beach sediment as “sand”, because of differences in the wave energy and also in the material available to any particular beach, grain sizes on beaches in California may range from very-fine grained sand to cobbles. Geologists and engineers classify sediment by size (e.g. silt, sand, pebbles) because different size materials behave very differently and these differences are of great importance in the formation and stability of

beaches. The Wentworth scale is most commonly used and classifies sediment by grain diameter in millimeters based on powers of two (Krumbein, 1936). According to this scale, sand is defined as all particles between 0.0625 mm and 2 mm in diameter, although sand is further broken down into fine-grained, medium-grained, etc. (Table 2.1). The phi scale was introduced 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. On other words, a grain size of 2 mm is equal to "2" so ø = -1; a grain diameter equal to 0.25 mm is equal to 1/4 or $1/2^2$ or 2^{-2} so ø=2. 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 (Table 2.1).

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. In an investigation of littoral transport processes and beach sand in northern Monterey Bay (Hicks, 1985), it was discovered that there is 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 actually remains on the beach. The littoral cut-off diameter is primarily a function of wave energy along any particular beach or stretch of coast.

Wentworth Scale Size Description	Phi Units ø	Grain Diameter (mm)
Boulder	-8	>256
Cobble	-6	64-264
Pebble	-2	4-64
Granular	-1	2-4
Very Coarse Sand	0	1-2
Coarse Sand	1	0.5-1
Medium Sand	2	0.25-0.5
Fine Sand	3	0.125-0.25
Very Fine Sand	4	0.0625-0.125
Silt	8	0.004-0.0625
Clay	12	<0.004

Table 2.1: Wentworth scale of sediment size classification

Studies along the coast of northern Santa Cruz County, which is a relatively high-energy, exposed coast, indicate a littoral cut-off diameter of ~0.18 mm (2.5ø), with very little sand finer than this remaining on the exposed beach. In southern California, where much of the coast is protected, the littoral cut-off diameter is finer, typically around 0.125mm (3ø). When estimating inputs into a sand budget or planning a beach nourishment project, it is important to consider the littoral cut-off diameter. Sand placed on the beach or entering a littoral cell that is finer than the littoral cut-off diameter will be carried offshore and will not remain on the beach itself.

What are Littoral Cells?

The coast of California can be divided into a number essentially self-contained littoral cells, often referred to as beach compartments (Figure 2.3; Inman and Frautschy, 1966). Littoral cells, have their own sources of sand, longshore transport (or littoral drift) that moves sand through the cell, and ultimately, a sink or sinks where sand is lost permanently from the littoral cell (Figure 2.4).

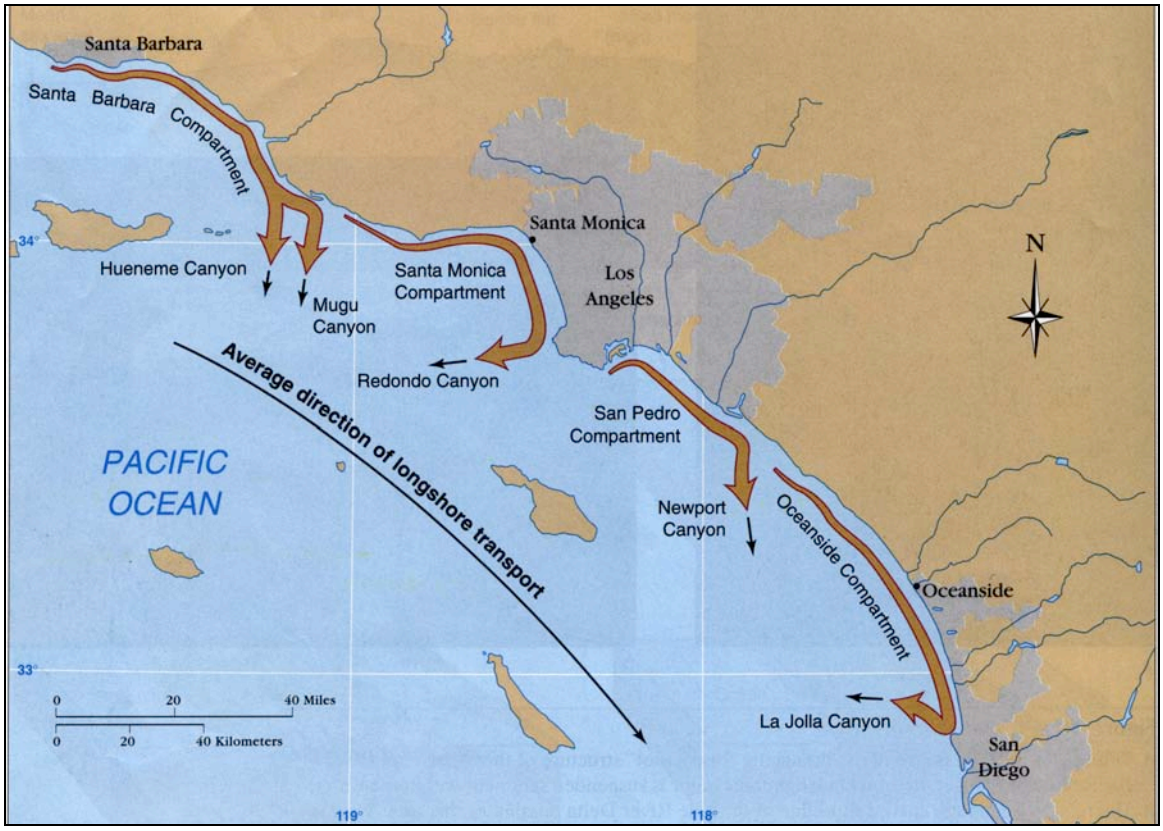

Figure 2.3: Littoral cells in southern California

A beach compartment often begins downcoast of a rocky headland or some littoral barrier or sink where sand from the adjacent upcoast cell has been trapped or lost, and therefore the upcoast supply of sand or littoral drift is restricted or minimal. Sand enters the littoral cell primarily from coastal streams

and bluff erosion, and is transported alongshore by wave-induced longshore transport. Ultimately, sand is lost from the compartment or cell either offshore into the head of a submarine canyon, onshore into coastal dunes, or in some cases, sand mining.

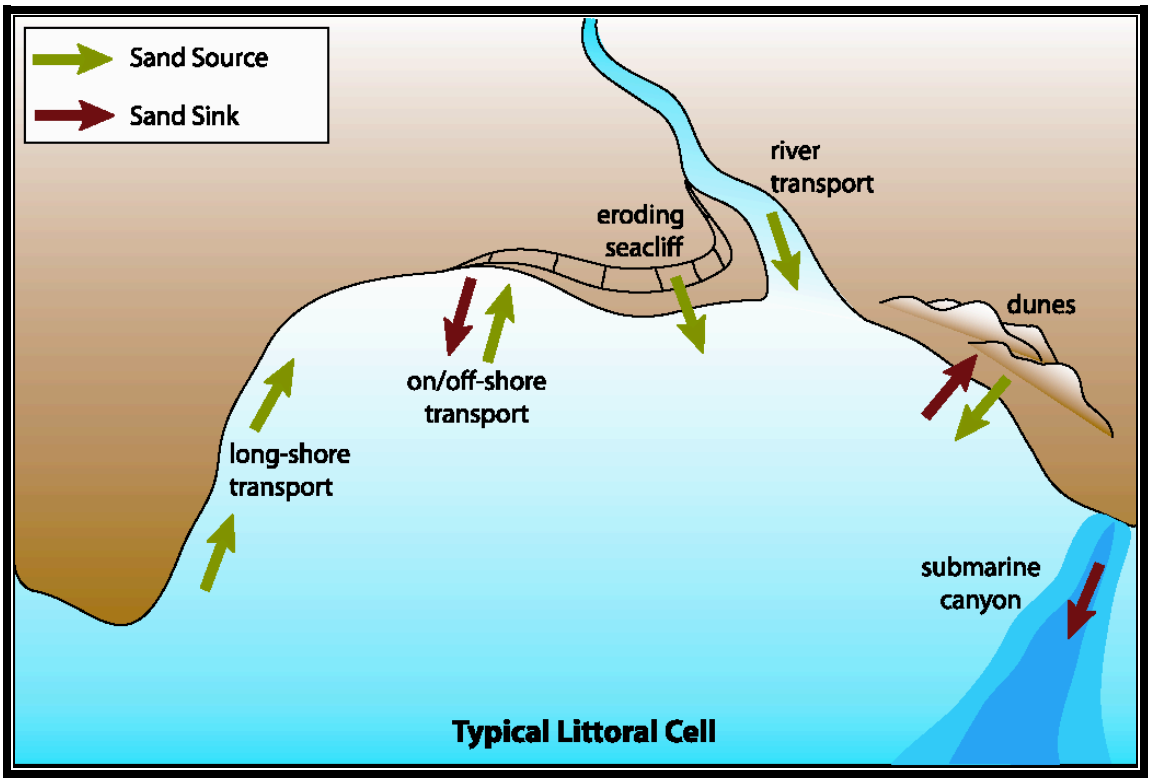

Figure 2.4: Sources and sinks in a typical littoral cell in California

During large storm events, sand may be either transported offshore or onshore from the seafloor seaward of the surf zone. Thus the immediate offshore area may be either a source or sink for beach sand, but for most littoral cells we simply don't have adequate information to quantify this transport and, therefore, the importance of the offshore area in littoral sand budgets.

Ideally, each littoral cell exists as a distinct entity with little or no transport of sediment between cells. It is believed that many headlands form nearly total barriers to littoral drift, but in other cases, during large storms, significant sand may be suspended and carried around points or across the heads of submarine canyons onto the beaches of adjacent cells.

The littoral cell concept (Inman and Frautschy, 1966) has been perhaps the most important discovery in the field of coastal and beach processes in the last 50 years, and it has enormous value in understanding coastal processes, sand input, output, storage and transport, and also provides an extremely valuable and useful framework for assessing any human intrusions into the coastal zone. Nevertheless, while boundaries have been delineated for California's major littoral cells (Figure 2.5; also see Chapter 4), there are still uncertainties and information gaps on these often well-studied cells: Where are the actual boundaries of each littoral cell? Does significant sand transport take place around or across these "boundaries"? What is the dominant littoral drift direction throughout each cell? These are a few of the questions that remain partially unanswered.

The application of a sand budget to the beach and 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. One of the first sediment budgets of a littoral cell was created for the region from Pismo Beach to Santa Barbara, estimating each sand input and output along this portion of the

central coast of California (Bowen and Inman, 1966). This budget has proven to be a valuable template for subsequent studies.

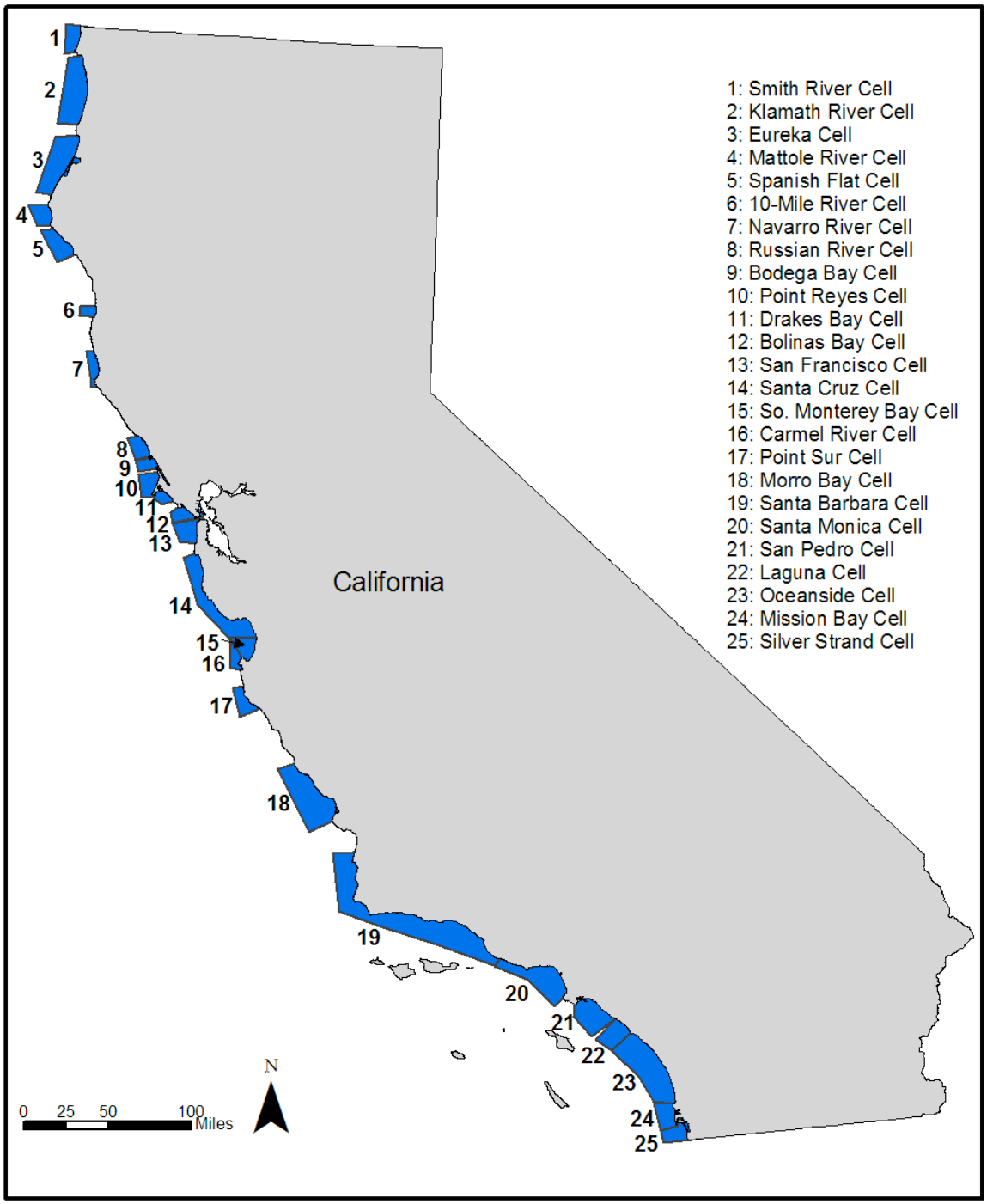

Figure 2.5. California's littoral cells

Lack of a qualitative and quantitative understanding of littoral cells and sand budgets has been apparent along the California coast for some time. The problems and costs associated with harbor dredging where jetties or breakwaters were 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 sediment behind dams in the coastal watersheds on the other, stem directly from our historic lack of understanding of littoral cells and their importance, or the failure to incorporate this type of information early on in the decision-making process in large watershed or coastal engineering projects.

Seasonal and Decadal Movement of Sand within a Littoral Cell

The shoreline within a littoral cell is dynamic, changing with the rhythms of the tides, seasons, and long-term climatic shifts, including the long-term fluctuations of sea-level. Beaches respond with great sensitivity to the forces acting on them, primarily wind and waves. Waves provide the energy to move sand both on- and offshore as well as alongshore. The beach is a deposit of well-sorted material that appears to be stable, but in reality, the beach and the sand in the nearshore zone are in constant motion on- and offshore and alongshore. This motion occurs underwater and on both short–term (individual waves) and long-term (seasonal and decadal) time scales.

Sea level changes as the tide moves in and out, changing the width of the exposed beach on a twice-daily basis in California. In addition to these daily variations, there are also long-term fluctuations in sea level as a result of global

climate change, which take place over hundreds and thousand of years. Sea level has been rising for about 18,000 years, and it is assumed by virtually all coastal and climate scientists that it will continue to rise into the foreseeable future. Over the past century, sea level has risen relative to the coastline in southern California by an about 20 cm, and at San Francisco by about 23 cm.

Beaches in California change on a seasonal scale with the changes in weather, storm intensity, and wave climate (Figures 2.6 and 2.7). Seasonal beach erosion is typically a recoverable process; beach sand lost each winter is generally replaced by the following summer. In the winter, the coast experiences an increase in storms and rainfall. The increased wave attack will erode the beach, and move sand into the nearshore where it is stored in sand bars. These sand bars will tend to reduce the wave energy hitting the shoreline because the waves will break farther offshore on the bars and lose some of their energy. As the winter storms pass and the intensity of the waves is reduced, the smaller, less energetic spring and summer waves begin to dominate. These smaller waves will tend to rebuild the beach with the sand that was moved offshore during the winter storms. Figure 2.7 shows a beach in central California during the during the summer months (A) when smaller waves have moved sand onshore to build a wide beach, and in winter (B) when large storm waves have narrowed the beach by moving sand onto offshore bars.

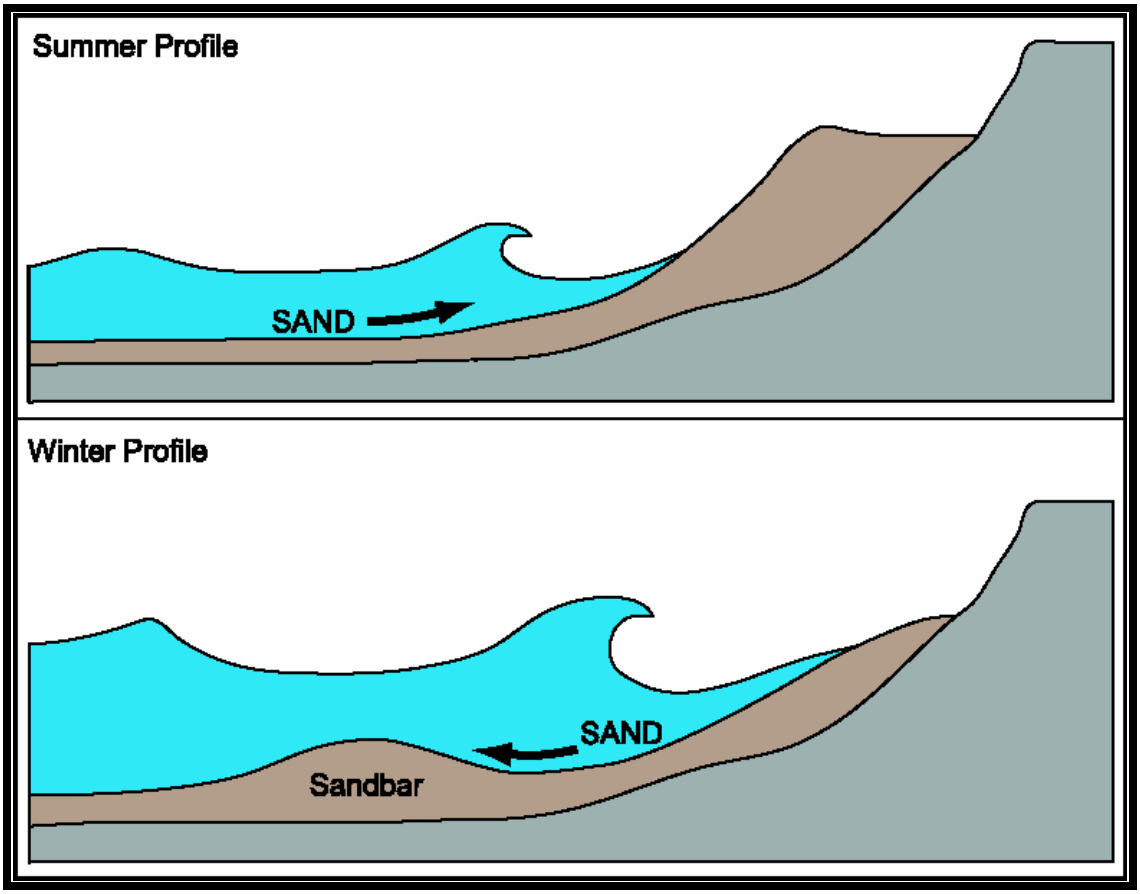

Figure 2.6: Summer Profile (also known as the swell profile) results from waves with low heights, and long periods and wavelengths. The beach is characterized by a steep foreshore and a broad berm (a terrace formed by wave action along the backshore of a beach). The winter beach profile (also known as the storm profile) is a response to higher waves, shorter wave periods, and shorter wavelengths. Waves become erosive and cut away at the berm, transporting sand onto offshore bars where it is stored until the following summer.

Over years and decades, beaches can erode or narrow, advance or widen, or remain in equilibrium, depending on the sand supply within a littoral cell. When sand supply is reduced through the construction of dams or large coastal engineering structures such as breakwaters or jetties, the beach can experience permanent erosion. This loss of sand and beach width may be recoverable, however, if the sand supply is restored.

Figure 2.7: Seasonal beach changes
A. Wide, summer beach at Its Beach in Santa Cruz (October 1997)
B. Narrow winter beach at Its Beach in Santa Cruz (February 1998)

Large-scale ocean warming episodes occur in the Pacific Ocean related to El Niño when mean sea level in California can be elevated by up to 15 cm or more for several months to a year. El Niño winters are characterized by more

frequent and vigorous storms over the Pacific, as well as an elevated sea level. During El Niño winters, severe beach erosion can result when large waves approaching from the west or southwest arrive simultaneously with very high tides. Research on changing climate conditions has identified periods lasting several decades when El Niño events are much more severe resulting in increased storm intensity and duration and ultimately increased cliff, bluff and beach erosion. The most recent cycle of intense El Niño events began in 1978. The severe winters of 1982-1983 and 1997-1998 caused severe beach erosion along California's shoreline and significant damage to oceanfront structures. Although the timing of these decadal-scale changes are not predictable, cycles of more frequent El Niño events have been recognized when storm activity, cliff erosion, and beach loss may be far more severe than during La Niña periods (characterized by cooler temperatures, and decreased storm intensity and rainfall) such as the interval from the mid-1940's to 1978.

Chapter 3: Development of Sand Budgets for Littoral Cells in California

Sand on the beach is in a constant state of flux, being moved on- and offshore and alongshore by waves and currents. Sand grains are transported to the beach from a variety of sources, including rivers and seacliff or bluff erosion, where they remain for a short time until they are entrained and moved as littoral drift. When the output or removal of sand exceeds the input of sand, beach erosion or narrowing results. Conversely, beach widening results when sand inputs exceed outputs, or also when some barrier to littoral transport (a groin or jetty for example) is constructed. Beaches are said to be in a state of equilibrium when sand sources or inputs are approximately equal to sand sinks or outputs.

A sand budget is an attempt to quantify changes in the sand volume along a stretch of coast by applying the principle of conservation of mass. In order to develop a sand budget, estimates must be made of the primary sand sources (credits) and sand losses (debits) for a stretch of shoreline. Balancing or creating a sand budget for a reach of coast is similar to balancing your checkbook. Sand sources such as fluvial inputs, seacliff or bluff erosion, longshore transport, and onshore transport from the nearshore can be thought of as deposits into your account. Sand sinks (i.e. submarine canyons, dune growth, longshore transport out of an area, offshore transport and sand mining) represent losses of sand to the system or debits to your account. The difference between the total volume of sand provided annually by all sand sources and the volume lost to all sinks for a

particular littoral cell will equal the rate of change in sand volume or storage within that region and provide insight on the stability of the beach or stretch of coast (Table 3.1).

A sand budget can be developed to represent short-term conditions, such as seasonal or yearly changes; however, when planning a large engineering project or alteration to the coast, it is best to construct a long-term sand budget that includes historic and present conditions. Many of the assumptions and errors involved in the data analysis and interpretation for the components of a sand budget can be reduced when a budget spans a greater length of time and averages out year-to-year variations in the components.

Sources of Sand	Sinks for Sand	Balance
Longshore Transport in	Longshore Transport out	Accretion
River Inputs	Offshore Transport	Erosion
Seacliff or Bluff Erosion	Dune Growth	Equilibrium
Gully Erosion	Sand Mining	
Onshore Transport	Submarine Canyons	
Dune Erosion		
Beach Nourishment		

Table 3.1: Sources and sinks of sand and the resulting balance in the development of a sand budget.

It is the balance of sand sources and sinks within each littoral cell that governs the long-term width of the beaches in California. If there is a significant reduction in the amount of sand reaching a particular stretch of coast, beaches should gradually erode or narrow. Conversely, if there is surplus of sand in a particular area, beaches will typically advance seaward, or widen.

Components of a Sand Budget

The first step in creating a sand budget is to develop a conceptual model for a stretch of coast or littoral cell. In a conceptual model, before calculations are made and data collected, the regional scope or boundaries of the littoral cell need to be defined and the potential sand sources, sinks and transport pathways need to be identified. This model will be the framework for the budget and may be based on an initial reconnaissance of a study area. The next step in developing a sand budget is to collect data, either through fieldwork or through a literature search to validate your conceptual model.

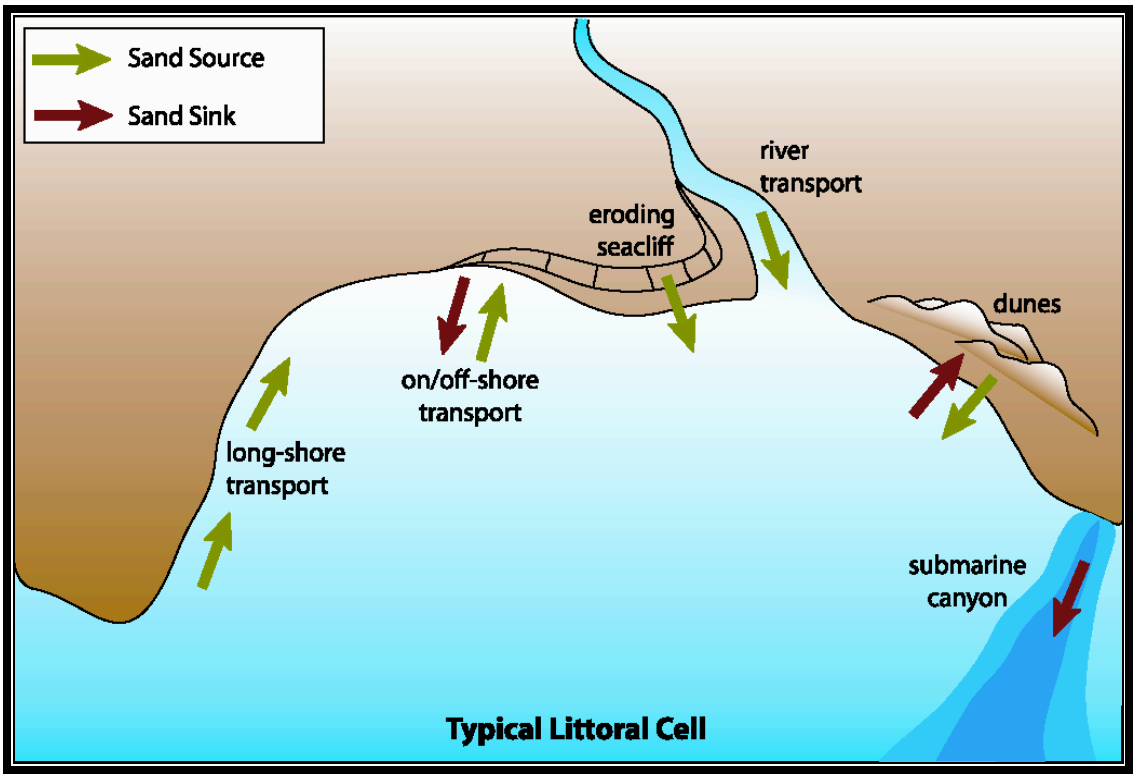

Figure 3.1: Sources and sinks for sand in a typical littoral cell in California

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. When developing a sand budget, it is best to perform a thorough literature search to find the most up-to-date information on each component. Calculations can also be made to estimate sand contributions from seacliff erosion, rivers, and dunes as well as other components of the budget. Along the California coast, most of the beach sand comes either from river and stream runoff with a lesser amount being derived from the erosion of coastal cliffs and bluffs. Sand is lost from littoral cells predominantly to submarine canyons, to sand dunes to a lesser extent, and perhaps to offshore transport beyond he surf zone. Sand mining directly from the beach was historically was a major loss for some littoral cells but much, but not all, of this has been eliminated. The following sections will give more specific information and difficulties or limitations on estimating the contributions from different sources and the losses to various sinks for sand in a littoral budget.

River Inputs (Source): Rivers contribute the great majority of sand to the beaches in California. Physical and chemical weathering slowly breaks down the rocks from coastal mountains into smaller fragments. The broken-down boulders, cobbles, gravel, sand, silt and clay move into mountain streams and creeks with rainfall, runoff, and slope failures where the sediments are sorted and transported downstream into larger streams or rivers. As the sediments travel down the many miles of the river or stream over subsequent months, they break-

down further and become smaller. Large cobbles and boulders are left upstream because the water does not have enough velocity or energy to transport them downstream. Eventually, the smaller particles of sand, silt and clay will reach the shoreline. The finer silt and clay particles are too fine to remain on the beaches, and are carried offshore by coastal and offshore currents where they are eventually deposited on the seafloor nearby or perhaps many miles offshore. Most sand-sized material will remain on the beach or and be moved by the littoral drift alongshore, thereby feeding the downdrift beaches. The finer-grained sand may, however, move into the nearshore zone.

The sand contributions for the majority of the coastal rivers and streams in California have been determined by using the daily measured values of water discharge or probabilities of discharge events (available on-line in the Water Supply Papers of the U.S. Geological Survey) to develop sediment-rating curves, or curves showing the relationship between water discharge and sand load for individual streams.

Sediment can be transported by streams, either as suspended load (the finer-grained sediment carried within the water, which makes it look muddy), or as bedload (the coarser material that is transported along the bed of the stream). Most of the suspended load usually consists of clay and silt, except during high discharge events when significant volumes of sand can be transported and delivered to the shoreline. Although the total amount of sediment carried as bedload is much less than that volume carried in suspension,

most of the bedload is sand and will contribute directly to the littoral sand budget.

Rating curves can be used to evaluate the total sediment yield each year from individual rivers and streams. Average sand yields (sediment that is sufficiently coarse to remain on the beach) have been calculated from these data for most of the rivers and streams in California (Willis and Griggs, 2003; Slagel, 2005). It has been determined that under historical or natural conditions that about 13-14.500,000 cubic yards of sand was being delivered annually to the coast of California from 37 major rivers and streams.

The methodology used in these two studies is believed to be the most reliable process currently available for determining the sand contribution to the shoreline from rivers; however it is not without error. Some gauging stations are often well upstream from the mouth of the river; thus, sediment loads may differ significantly between the gauging station and the shoreline.

Sediment delivery by rivers to California littoral cells has also been shown to be extremely episodic. Most of the sediment for any particular stream is discharged during several days of high flow each year. Additionally, sediment 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 (sand, silt and clay) on December 23, 1964, 18% of the total sediment load of the river during the previous ten years. This one-day discharge is greater than the average annual suspended sediment discharge of

all of the rivers draining onto the entire California coastline. Little or no sediment discharge data may exist, however, on some streams, 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, particularly for 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 the dry periods by a factor of about three, and the mean annual suspended sediment flux during the wet periods exceeded the dry periods by a factor of about five (Inman and Jenkins, 1999).

At their best, however, data on fluvial discharge of sand 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 littoral budgets in California.

Reductions to Fluvial Inputs: Damming of rivers or streams will reduce the sediment delivery to the coast by both trapping sand in the reservoirs and also by reducing the peak flows that transport the greatest amount of sediment. Most of California's large dams, under good management, have reservoir

capacities sufficient to absorb all incoming water during a normal winter, releasing only low flows to downstream areas As a result, the magnitude and frequency of peak flows are reduced, which decreases the ability of the river to transport material downstream (Figure 3.2). Dams act as complete barriers to bedload (the sand transported along the bottom of the stream) and also usually trap most of the suspended sediment load, except during large flood events when flows overtop the dam or pass through the spillway. The average trapping efficiency or the amount of suspended sediment trapped by the dam, for most coastal dams in California is about 84% (Brune, 1953; Willis and Griggs, 2003).

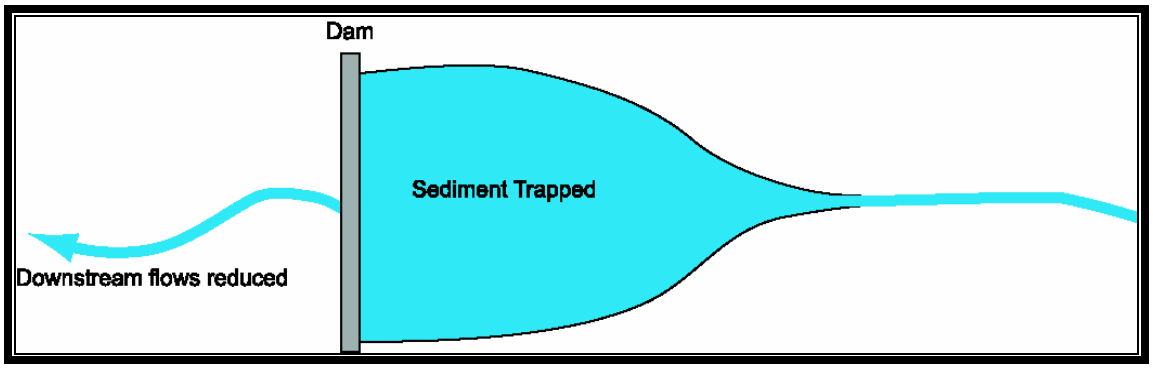

Figure 3.2: Dams will trap sediment, thereby preventing it from moving downstream to the shoreline, in addition to reducing the flow of the river and thus its ability to transport sediment.

Recent work by Willis and Griggs (2003) and Slagel (2005) indicate that the present day delivery of sand to the shoreline has been reduced to about 10 – 11,000,000 yds^3/year, or approximately a 23-25% reduction from natural conditions, due to the more than 500 dams on coastal streams, the great majority of this reduction concentrated in southern California (Table 4.2)

It has also been shown recently that sand mining in Northern California coastal watersheds and along stream channels has removed about 9 million yds^3 (11,000,000 t) of sand and gravel annually on average, and similar operations in Southern California have removed about 46.5 million yds^3 (55,800,000 t) annually on average (Magoon and Lent, 2005). It is unclear how much of this sand and gravel would naturally be delivered to the coast by rivers, but sand mining may play a major role in the reductions of fluvial sand delivery to the shoreline.

If sand supply from rivers is continually reduced through impoundment behind dams, as well as through sand and gravel mining from stream beds, then beaches should eventually be deprived of a significant portion of their predominant sand source, and over decadal time scales, beaches should narrow or erode, assuming there is no change in littoral transport rates. Littoral transport rates are a function of the amount of wave energy and the angle of wave approach, as well as the sand available for transport. More wave energy and a greater angle of wave approach will generate larger littoral drift rates.

Figure 3.3 illustrates beach narrowing resulting from a reduced sand supply. In the figure, a simplified littoral cell is presented with a single river as the only sand source, thus ignoring sand contribution from cliffs and onshore transport. If the amount of sand delivered by the river is reduced, and the potential volume of sand able to be moved as littoral drift remains the same, then the downdrift beach volume or width should decrease over time.

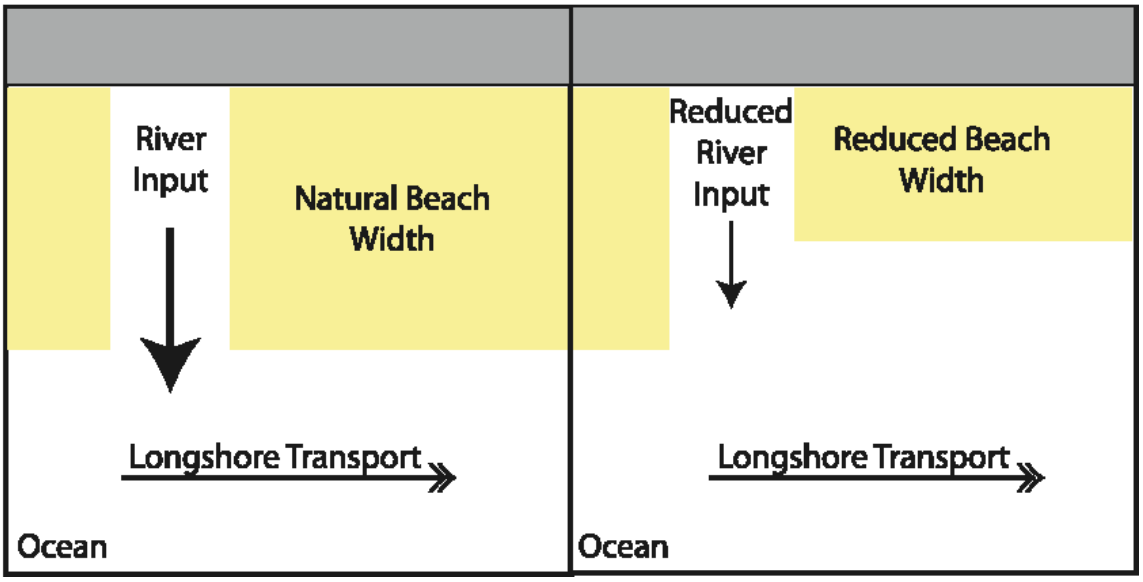

Figure 3.3: The effects of a reduction in sand supplied by rivers due to damming. With a constant potential littoral drift volume or longshore transport, beaches would be expected to narrow with a reduction in river input.

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, may contribute sand to California's beaches. Coastal cliffs that consist of materials such as sandstones or granite that break down into sand-sized grains will contribute sand to the beaches. Fine-grained rocks that consist of silt and clay (shales or mudstones), on the other hand, will not contribute significantly to the beach.

The geology of the seacliffs along the coast of California varies widely alongshore and, therefore, the amount of sand contained in the cliffs or bluffs is different from place to place. Typically, where the coastal cliffs consist of uplifted marine terraces, there is an underlying, more resistant bedrock unit, which is typically some type of sedimentary rock, 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 combined to arrive at a total contribution to the beach for a larger area, such as a specific littoral cell.

The annual production of littoral sand (sand sufficiently coarse enough to remain on the beach) 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:

$$Qs\ (ft^3/yr) = L_c * E * (H_b * S_b + T_t * S_t)$$

in which L_c is the alongshore length of the cliff (ft); E is the erosion rate (ft/yr); H_b is the bedrock height (ft); S_b is the percentage by volume of beach-size material in the bedrock; T_t is the thickness of the terrace deposit if present (ft); and S_t is the percentage by volume of beach-size sand in the terrace deposit (Figure 3.4).

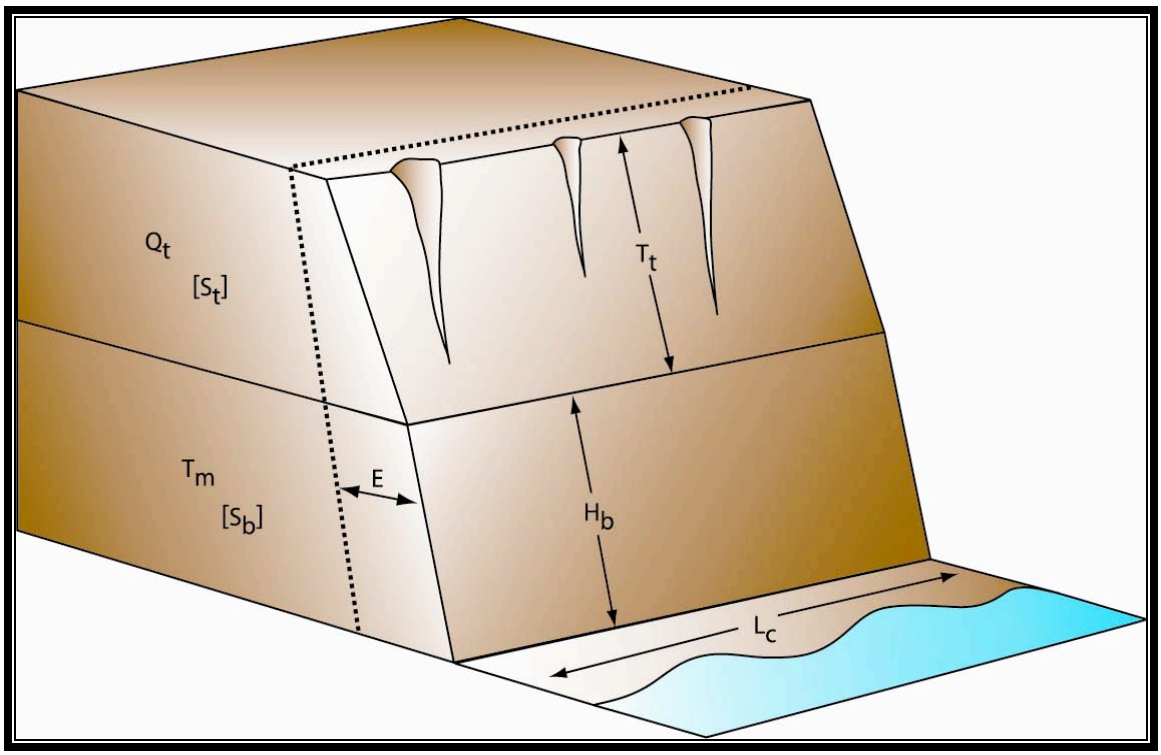

Figure 3.4: Seacliff showing the components involved in determination of sand contribution, in which L_c is the alongshore length of the cliff (ft); E is the erosion rate (ft/yr); H_b is the bedrock height (ft); S_b is the percentage of sand size material in the bedrock; T_t is the thickness of the terrace deposit (ft); and S_t is the percentage of sand in the terrace deposit. Tm (Tertiary Marine) represents the geology of the bedrock, and Qt (Quaternary Terrace) represents the geology of the capping terrace deposit.

The methodology for determining sand contributions from seacliff erosion is simpler than that for determining river contributions; however, these calculations 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 cliff or bluff failure. Seacliff erosion rates are typically determined by very precisely comparing the position of the cliff edge over time on historical stereo aerial photographs (Griggs, Patsch and Savoy, 2005). This is not a straightforward process, however. Ideally, historical

aerial photos spanning at least 50 years are desirable. The photos need first to be corrected or rectified due to distortion. Next the cliff edge or reference feature, which may be obscured or difficult to delineate, needs to be precisely located and compared on a series of photographs spanning as much time as possible, to get a representative a measurement of erosion change. Each of these steps or processes involves some error.

The use of LIDAR (light detection and ranging) which involves the application of a laser system for measuring 3-dimensional bluff topography, either from an airplane or from the beach) has been used on a somewhat limited basis since about 1997, to very precisely measure erosion rates and changes. This new approach is still not widely available but it provides for much more precision than was previously possible, although we cannot use this on historic photographs so it is confined to recent changes.

On a state-wide basis, beach sand contributions from seacliff erosion tend to be much less than stream inputs, although they may be very important locally where cliffs are rapidly eroding and very sandy, and where there are no large streams (Runyan and Griggs, 2003). While bluff erosion contributes less than one percent of the sand to the Santa Barbara littoral cell, erosion of the bluffs is believed to contribute about 31% of the sand to the Laguna cell and 60% of the sand to the Mission Bay cell.

Recent research in the Oceanside littoral cell utilized both the composition of the sand in the bluffs and on the beaches, as well very precise LIDAR

measurements of coastal bluff retreat over a relatively short 6-year period and concluded that bluffs may contribute 50% or more of the sand to the beaches of this area.

Beach Nourishment (Source): Beach nourishment is used to describe the sand added to a littoral cell by some human activity that would not have otherwise been placed on the beach. It is a way to artificially widen otherwise narrow beaches and has occurred more frequently in southern California. Historically nourished sand has come from a variety of sources, including dredging of coastal lagoons, bays or estuaries for the creation or expansion of marinas or harbors, dredging of river channels, coastal construction projects where dunes or other sand is excavated and placed on the beach, and also from dredging of offshore areas. Most of the projects completed in the past served dual purposes, the primary purpose of creating a marina, clearing a river channel or excavating a construction site, and the secondary purpose of nourishing or widening the beach. In some projects completed 30 or 40 years ago, the beach was seen simply seen as a convenient sand disposal site.

When developing a littoral budget, sand from offshore sites, or from coastal or inland sources, is considered an additional source of sand, and thus is labeled nourishment. Harbor entrance bypassing operations or channel maintenance dredging, however, where sand already in the littoral system is simply moved across or out of an entrance channel is not considered new

sources of sand because it is simply a way to move the sand already in the budget to a new location within the cell.

Cross-shore exchange (Source/Sink): Potential exchange of sand between the nearshore and offshore areas, including the inner continental shelf, is the most challenging and poorly evaluated element in most sand budgets. With the large shelf areas typically involved, a small increase in the thickness of the sediment veneer over an extensive area can produce a large volume of sand in storage. Cross-shore transport can represent a net gain or loss for the beach. A comparison of sediment composition (for example the distinct minerals contained in the sand) between beach, 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."

Whether or not sand is moved onshore or offshore is controlled by factors such as wave energy and tidal range, bottom slope and the grain size of the sand. In order to thoroughly evaluate this component it would be necessary to have data on the precise thickness or depth of beach-sized sand over a large

offshore areas and to know how this has changed over time. We simply don't have these data anywhere and it would require a long-term study to determine how the distribution of sand changes over time. In developing littoral sand budgets, it is often assumed that net cross-shore exchange of sand is zero, such that the volumes of sand transported on- and offshore are balanced, unless sediment data are available on a particular area of interest. In other areas, however, any unaccounted for losses are usually ascribed to offshore transport.

Dune Growth/Recession (Sink/Source): Sand dunes occur adjacent to and inland from beaches at many locations along the coast of California. Dunes are created where ample sand is available with a persistent onshore wind and a low-lying area landward of the beach where the sand can accumulate. Typically if the shoreline is backed by seacliffs, dunes will not have any area to accumulate or migrate, and thus, will not grow to any significant size. In many areas of California, such as the area north of Humboldt Bay, southern Monterey Bay, Pismo Beach area, and in areas along Santa Monica Bay, sand has blown inward from the beach and created large dune complexes. It is permanently lost from the shoreline, constituting a significant sink to the cell. For example, it has been estimated that an average of 200,000 yd^3/yr of sand is blown inland and lost permanently from the beaches along the 35-mile coastline from Pismo Beach to Point Arguello (Bowen and Inman, 1966; Figure 3.5). In areas such as the Southern Monterey Bay littoral cell, however, dune erosion and recession play an

important role as a sand source to the littoral budget, partially making up for some of the sand that was lost from the shoreline historically through mining.

Figure 3.5: Pismo Dunes in San Luis Obispo County
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Dune migration, growth and erosion (or deflation) can be measured from aerial photographs or in the field; these rates can be converted into sand volumes by measuring the dune width and height. Although it is most common that dune growth acts as a sink in a littoral cell budget, sand may be blown onto the beach from an inland area (representing a source). Dune growth and deflation often introduce a time element into a cell budget. One major storm can erode the portion of the dunes closest the ocean (called the foredune),

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.

Losses into Submarine Canyons (Sink): Submarine canyons that extend close to shore (such as La Jolla, Mugu, Newport and Monterey submarine canyons (Figure 2.4) serve as effective barriers to littoral drift and terminate most littoral cells in California. These canyons are the largest permanent sink for sand in California. Sand accumulates in the mouth of the submarine canyons and through underwater sand flows or turbidity currents is essentially funneled away from the beach and typically deposited in deep offshore basins.

It is believed an average of over a million cubic yards of sand annually is transported down into Mugu Submarine Canyon, thus terminating the Santa Barbara littoral cell. Monterey Submarine Canyon (Figure 3.6), located in the center of Monterey Bay, is one of the world's largest submarine canyons at over 6,000 feet deep. An average of at least 300,000 cubic yards of sand is permanently lost annually down this canyon. For the development of a sand budget, the sand arriving at the end of a littoral cell, after all the sources and other sinks have been accounted for, is assumed to be directed into and lost to a submarine canyon, where one exists and reaches close enough to the shoreline to trap littoral drift.

Figure 3.6: Monterey Submarine Canyon

Sand Mining (Sink): Sand and gravel have often been 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. Sand mining along the beaches of California and Oregon began in the late 1800s when there seemed to be an overabundance of sand and no obvious impacts from mining. Overall in northern California, from the Oregon border to the Russian River, about 11 million tons of sand and gravel are

removed each year from the coastal streambeds (Magoon and Lent, 2005). In southern California the total is nearly 56 million tons annually, primarily in the greater Los Angeles and San Diego areas.

Beach or streambed sand mining has historically been a large sink for beach sand in some specific locations that was difficult to quantify for the purposes of a sand budget. Due to the proprietary nature of sand mining operations, it has been difficult to gather information on specific mining practices for a given river or beach within a littoral cell. Information on mining should be included in long-term sand budgets when available. While there are still extensive sand and gravel mining operations along many streambeds in California, direct removal of sand from the beach, for the most part, along the coast of California was terminated by the early 1990's. However, mining of the back beach still occurs near Marina in southern Monterey Bay (Figure 3.7).

Harbor Dredging (check point): California's four large harbors and 21 small craft harbors (Figure 3.8) serve as constraints, or check points, when developing sand budgets. Half of the littoral cells in California (10 of the 20 cells) contain at least one harbor that serves as an effective sand trap. These coastal sand traps, however, are very different from dams and reservoirs, which keep sand from ever entering the littoral system. Much of the 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

Figure 3.7: Sand mining directly from the beaches of southern Monterey Bay (2005). Photo © Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

jetty and breakwater configuration and geometry of some harbors (e.g. Ventura and Channel Islands harbors; Figure 3.9) were built to trap sediment before it enters the harbor's 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 potential sand trap 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

some natural bypassing may occur through littoral drift, especially for those harbors that were designed without a specific trapping area, harbor dredging

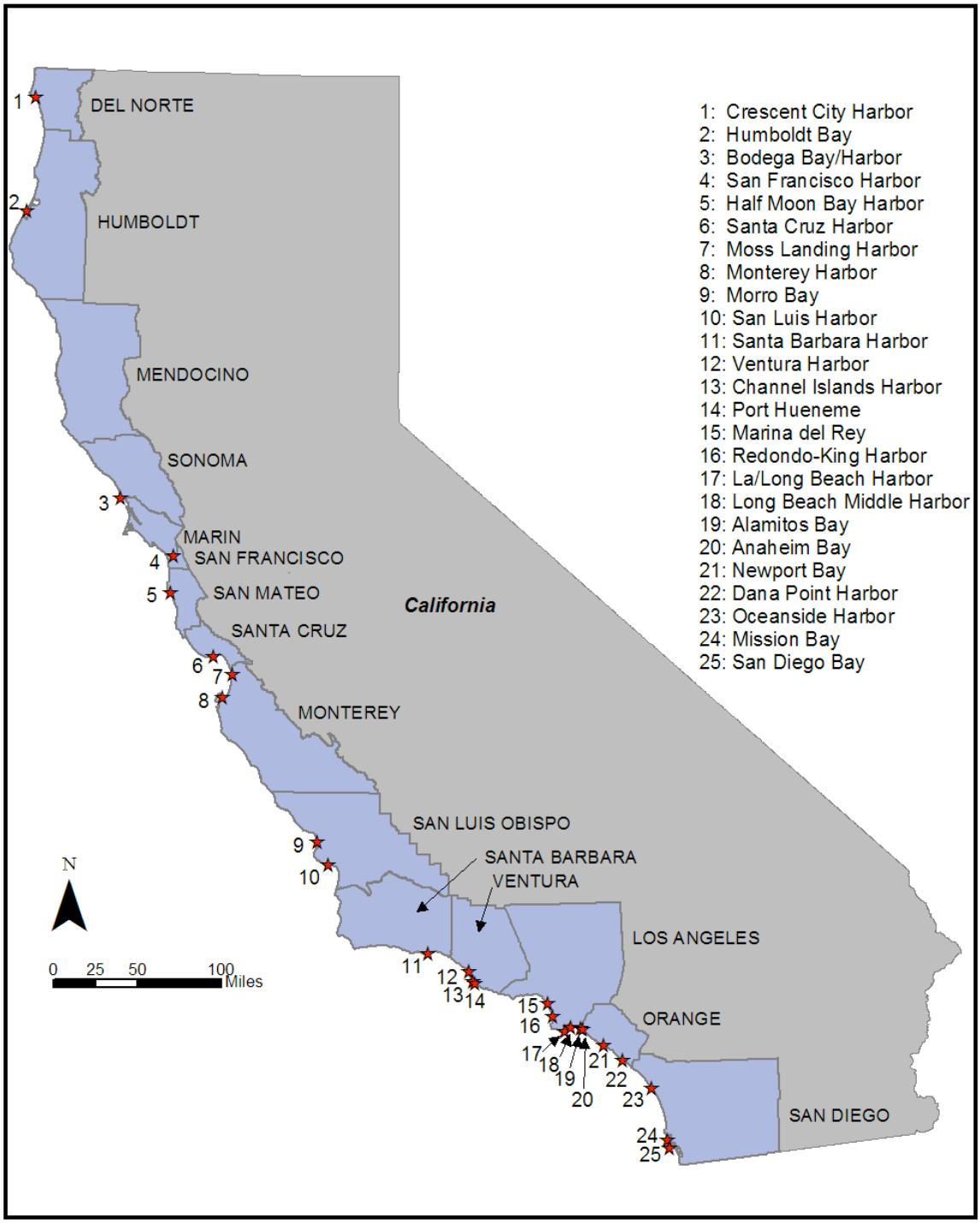

Figure 3.8: California's harbors and location by county.

Figure 3.9: Ventura Harbor: maintenance dredging in 1997

records are the most dependable numbers available for determining or estimating long-term annual gross and, occasionally, net littoral drift rates. When developing a sand budget for a littoral cell, there must be 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. Some littoral cells 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.

It is important to understand, however, that some inherent errors are involved when using harbor entrance dredging volumes to estimate longshore transport rates, and 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. There are also harbors, Oceanside, for example, where detailed studies indicate that littoral drift reverses seasonally, such that sand can be dredged twice. Significant bypassing of fine-grained sand does take place at Oceanside, and sand appears to have been transported offshore and formed a permanent bar (Dolan, Castens, et al., 1987; Seymour and Castel, 1985).

It is believed that the margin of error involved, however, in estimating dredged sand volumes is still significantly lower than the error associated with quantifying the annual volumes of most of the sand sources and sinks for a littoral cell (such as the sand contribution from streams and cliff erosion and sand lost to submarine canyons). For most locations, harbor entrances form nearly complete littoral traps, and where long-term data exist, harbor dredging records are the most dependable and representative numbers for determining long-term annual gross and occasionally net littoral drift rates, and for providing a check point for a littoral cell sand budget.

Chapter 4: Summary of Sand Budgets for California's Major Littoral Cells and Reductions to Sand Supply

The beaches of southern California are intensively used recreational areas generating billions of dollars of direct revenue annually. These wide, sandy beaches, used by people playing volleyball and sunbathing, jogging and surfing, are the quintessential image of southern California. Wide, sandy beaches, however, were not always the natural condition. 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 (Flick, 1993). Without human influence, many of the beaches along this coast would be, for the most part, narrow and difficult to access. Narrow beaches would be insufficient for the recreational demands imposed on the beaches today. The rate at which sand was historically added to these beaches, however, has been diminishing over the past 30 years, fueling the public's perception of 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 a reduction in beach nourishment projects.

Sand is naturally supplied to the beaches in California's littoral cells from a combination of river discharge, seacliff erosion, and dune deflation or erosion. In addition, sand has been added to the beaches historically through various beach nourishment projects. Sand budgets are presented in this summary for the major

littoral cells in California (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; Figure 2.5) showing the importance of each source of beach material and the extent to which the sand supplied to these cells has been reduced through the armoring of seacliffs, the damming of rivers, and also through sand mining.

Table 4.1 gives an overview of the relative importance of individual sand sources for each littoral cell, in addition to the overall importance of each component to the total littoral cell budget for the entire state. These data were developed for and derived from a recent more detailed companion study, which quantified the sand budgets for all of California's major littoral cells (Patsch and Griggs, 2006). Under present-day dammed conditions (excluding beach nourishment), and based on all data published to date, fluvial inputs constitute about 87% of the sand entering California's major littoral cells, and contribute 90% of the sand to southern California (from Santa Barbara to the international border). Seacliff erosion contributes 5% of the sand to the major littoral cells statewide and about 10% of the sand reaching the beaches in southern California (excluding beach nourishment). Dune recession statewide accounts for 8% of the littoral sand (excluding beach nourishment).

When beach nourishment is taken into account as a contributing source of sand, the relative importance of rivers, bluffs, and dune erosion statewide drops to 72%, 4% and 7% respectively in California's major littoral cells, with beach

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 California 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 California	90%	10%	0%	N/A	3,016,000

*Table 4.1: Summary of the actual (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 49% of the sand in the Oceanside littoral cell. This category is not accounted for in this table. (For sources for these data see Patsch and Griggs, 2006)*

nourishment accounting for the remaining 17% of the sand input. 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 4.2 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 sediment supplied to southern California is from the damming of rivers, which contribute the majority of sand to the littoral cells. Damming has reduced the sand reaching the beaches of southern California by about 46% of the natural fluvial sediment yield, which is equal to a reduction of nearly 2.4 million cubic yards of sand annually (Willis and Griggs, 2003). 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, still less than 7% of the total sand input to all of these littoral cells.

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 yd^3/yr	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 California Total	Reduction yd^3/yr	2,297,000	35,000	2,332,000	1,338,000	-994,000
	Percent reduction	47%	10%	44%		

Table 4.2: 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).

Chapter 5: Discussion of Beach Nourishment in California

Beach nourishment is the introduction of sand onto a beach and is a mechanism to artificially widen beaches that may be naturally or those where the natural supply of sand has been significantly reduced through human activities. Beaches can be nourished to increase their width by depositing sand upcoast, directly on a beach, or just offshore of the beach in the nearshore zone. Nourished shorelines provide two primary benefits: increased area for recreation, and greater protection of the coastline against coastal storms. Other potential benefits include increased tourism revenues, increased shoreline access, reduced need for hard protective structures, enhanced public safety and restored wildlife habitats.

Beach nourishment in California has been concentrated primarily in the southern part of the state. Flick (1993) summarized the history of beach nourishment in southern California and determined that over 130 million yds^3 of sand was added to those beaches between 1930 and 1993. About half of this amount was divided evenly between the Santa Monica and the Silver Strand littoral cells where the beaches widened significantly in response to this nourishment. Wiegel (1994) prepared a very thorough evaluation of ocean beach nourishment along the entire USA Pacific Coast, although the report is mostly about Southern California because of the numerous beach nourishment projects that have taken place there.

The California Beach Restoration Study was completed in 2002 and was a comprehensive assessment of California's beaches and their economic benefits, beach nourishment and restoration, as well as an evaluation of the major sources of sand to the state's beaches and how these had been impacted by human activity (http://www.dbw.ca.gov/beachreport.htm).

Opportunistic beach nourishment, which has provided the majority of sand historically used for beach nourishment in southern California, occurs when sand from a harbor development or expansion project, from excavation for a large coastal construction project (El Segundo Power Plant or Hyperion Sewage Treatment Plant construction, for example) is placed on nearby beaches. In other words, this sand is a byproduct of some other construction or maintenance project that was not undertaken with beach replenishment or nourishment as a specific goal, but rather as an added benefit.

Sand bypassing systems often operate at harbor entrances and serve the dual purposes of maintaining the entrance channel and nourishing the downdrift beach. If sand is not derived from an "opportunistic" source, it may be trucked from inland sources or dredged from the seafloor offshore. Some beach nourishment projects have combined the placement of sand with the construction of groins or detached breakwaters to retain the sand. These projects tend to be more successful, simply because the high to very high littoral drift rates that characterize most of California's shoreline will tend to move any

additional sand alongshore. Different constituencies, however, often perceive the success or failure of a beach nourishment project, differently.

Beach nourishment, unless it accompanied by some structure or mechanism of holding the sand in place (groins, for example), may not provide a long-term solution to narrow beaches or beach erosion in California. In the absence of any human-induced reductions to littoral sand supply, beaches over the long-term will tend to approach some equilibrium size or width (e.g. a summer width that will vary somewhat from year to year). This width is a function of the available littoral sand, the location of barriers or obstructions to littoral transport (Everts and Eldon, 2000; Everts, 2002), as well as the potential for littoral drift, which is related to the amount of wave energy incident on the beach, the angle of wave approach and the coastline orientation. In northern Monterey Bay, for example, because of the direction of dominant wave approach and the coastline orientation, those shorelines oriented northwest-southeast, or north-south, such as Santa Cruz Main Beach, Seabright Beach, or the inner portion of Monterey Bay, have wide well-developed beaches (Figure 5.1). In contrast, where the coastline is oriented northeast-southwest (from Lighthouse Point to Cowell's Beach and the Opal Cliffs shoreline between Pleasure Point and New Brighton Beach, for example), and where no significant littoral drift barriers exist, beaches are narrow to non-existent because littoral drift moves the sand along this stretch of coast rapidly without any retention.

Figure 5.1. The coastline of northern Monterey Bay at Santa Cruz illustrating how the orientation of the coastline determines whether or not a beach forms.

One comprehensive analysis of the longevity of beach nourishment in California (Leonard and Dixon, 1990) concluded that 18% of nourishment projects “survived” less than a year, 55% lasted one to five years, and only 27% remained after five years. Projects with the longest life spans have often been coupled with beach retention structures such as groins, or are routinely maintained with additional fill. In this analysis, the authors considered the

amount of sand that remained on the visible or exposed beach as a measure of success.

In California, 58% of the nourishment projects analyzed by Leonard and Dixon (1990) were in conjunction with harbor dredging and maintenance, 16% were federally funded beach erosion control projects, 16% were state and locally funded beach erosion control projects, and the remaining 10% of projects were funded privately.

Factors affecting the longevity of a beach nourishment project

It has often been assumed that the important parameters in the durability or longevity of a beach nourishment or replenishment project include the alongshore length of the nourishment project, the density or volume of fill placed, grain size compatibility with the native beach, the use of sand retention structures such as groins in conjunction with sand placement, and storm activity following nourishment. Those nourishment projects that had the greatest alongshore dimensions have been shown to last longer than shorter beach fills. Lengths of California's historic beach nourishment projects range from two tenths of a mile at East Beach, Santa Barbara, to six miles at Long Beach, with an average length of 1.2 miles (Leonard and Dixon, 1990).

Fill Density: Density of the fill refers to the volume of sand per unit length of shoreline. The longevity of a nourishment project has often been assumed in the past to be directly related to fill density, with greater fill densities

yielding longer life spans. However, a comparison of fill densities and life spans for 13 nourishment projects along the Gulf Coast some year ago (Dixon and Pilkey, 1989), showed no clear correlation. In California, the initial fill densities range from 20,000 cubic yards per mile to 2,128,000 cubic yards per mile.

Grain Size: Grain size compatibility between the native beach and the fill material is also perceived to be an important factor in the longevity or durability of a nourished beach. Beach fill must be compatible with the grain sizes of the native sand (as coarse as or coarser than the native sand) such that the waves will not immediately carry the sand offshore. Fill sand must be coarse enough to remain on the beach.

Structures: Coastal structures aimed at retaining sand, such as groins, or detached offshore breakwaters, have been successful in extending the life span of nourishment projects. For example, groins throughout the Santa Monica littoral cell, and groins placed on beaches in Capitola, Ventura, Redondo Beach and Newport Beach have all been successful at stabilizing beach fill projects. However, if there is not enough sand in the system to begin with, groins will not be effective, as was the case at Imperial Beach where a series of groins has not been enough to combat erosion. Groins will continue to trap littoral drift in the years following a beach nourishment project, thus maintaining the updrift beach. Groins must be considered on a regional scale, however. While beaches updrift of groins will be stabilized, or widened, beaches downdrift of a groin may experience erosion once their sand supply is cut-off. A series of groins along the

shoreline of interest, in conjunction with beach nourishment, may be an effective way to address downdrift beach erosion.

Offshore breakwaters have been widely used in Europe, and in a few locations in the United States, to stabilize or widen beaches by reducing wave energy and littoral drift in the lee of the breakwater. These offshore structures can be either slightly submerged, at sea level, or slightly above sea level. The offshore breakwater at Santa Monica is perhaps the best example of the effects of such a structure in California, where the beach landward of the breakwater significantly widened (Figure 5.2). The Santa Barbara breakwater was initially constructed in 1928 as a detached offshore structure. Although the purpose of the breakwater was to provide a protected anchorage for boats, the wave shadow quickly widened the beach landward of the structure. While this benefited the shoreline and beach users, it served to reduce the area for boat anchorage, which was the primary intent of the structure. Within a few years the breakwater was extended to the shoreline.

Detached offshore breakwaters thus can effectively reduce wave energy at the shoreline, thereby widening or stabilizing otherwise narrow or eroding beaches. They are not without their impacts, however: high construction costs, navigation hazards for vessels, dangers for recreational coastal water users, as well as a reduction in sand transport to down coast beaches are all important considerations.

Figure 5.2. Offshore breakwater at Santa Monica where beach has widened in protected area behind breakwater (2004). Photo © Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org

Storm Intensity: The life span of beach nourishment projects has been correlated with storm intensity to which a fill is exposed. Large or extreme storms, such as those that have occurred during El Niño years, have caused increased beach erosion, whether nourished or not. Sand removed from the beaches during these large storm events is often deposited on offshore bars where it is stored until the smaller waves associated with the summer months carry the sand back to the beach. During conditions of elevated sea levels and very large waves, sand may be transported offshore into deep enough water where summer waves cannot move the sand back onshore. Longshore transport may also increase with the larger storm waves, thus reducing the residence time

of the sand on a nourished beach. During the strong 1997-98 El Niño, however, monthly beach surveys collected along 22 miles of Santa Cruz County coastline showed that although the beaches experienced extreme erosion during the winter months, by the end of the summer of 1998, all but one had returned to their original pre- El Niño widths (Brown, 1998).

Issues Involved with Beach Nourishment

While beach nourishment appears to be an attractive alternative to either armoring the coastline with seawalls, riprap or revetments, or to relocating threatened structures inland, it has a number of issues or considerations that need to be carefully evaluated and addressed. In California, littoral cells span large stretches of the coastline, from 10 miles to over 100 miles in length, and, in most locations, experience high littoral drift rates (from 150,000 yd^3/yr to over 1 million yd^3/yr). As a result, the life span or longevity of sand placed on a particular beach is likely to be fairly short (less than a single winter, in some cases) due to the prevailing winter waves transporting the sand alongshore as littoral drift.

In addition, potential difficulties or impacts associated with beach nourishment in California include cost, financial responsibility for the initial project and subsequent re-nourishment, the source and method for obtaining sand, transportation of large quantities of sand to the nourishment site, and the

potential smothering or temporary loss of marine life or habitats when placing the sand.

The availability of large quantities of beach compatible sand is a significant issue that has not been completely resolved. Sand exists offshore in large volumes but it may not always be beach compatible and there are environmental and habitat issues that need to be evaluated and possibly mitigated. Some offshore areas are protected, such as the 400 miles of coastline included with the Monterey Bay National Marine Sanctuary, and for which dredging sand from the seafloor is a complex issue with a significant list of environmental concerns and probable opposition.

While consideration is being given to removing sediment from behind dams that are now essentially completely filled (the Matilija Dam on the Ventura River and the Rindge Dam on Malibu Creek, for example) and placing this in the beach, there is not yet any agreed upon approach for accomplishing this objective. Dam removal followed by natural fluvial transport, trucking, and slurry pipelines have all been studied and each has their costs and impacts. Even though this sediment would have been delivered to the shoreline by these streams under pre-dam natural conditions, accomplishing the same “natural process” today is far more complex. The release of all of the impounded sediment would overwhelm any downstream habitats that are now being protected. In addition, the present Army Corps of Engineers guidelines do not

normally allow any sediment to be placed on beaches when the amount of fines (silt and clay) is over 20% (the so-called 80:20 rule, or acceptable sediment for beach nourishment must consist of at least 80% sand and no more than 20% silt and clay). Unfortunately, however, the sediment transported by streams and trapped behind dams doesn't follow this 80:20 rule and contains far more than 20% silt and clay. As a result, most sediment impounded in reservoirs wouldn't be acceptable to the Corps for beach nourishment by present criteria, even though these same streams naturally discharge such sediment every winter to the shoreline, where waves and coastal currents sort out all of this material.

If inland sources of beach compatible sand can be located, approved, and transported to the coastline, there are additional challenges of actually getting the material onto the beach and spreading it out in a timely manner. A 200,000-yds^3 beach nourishment project, for example, would require 20,000 10-yds^3 dump trucks.

In California, obtaining sand from an inland source to place on the beach is far more costly than sand from offshore sources primarily due to significantly higher removal and transport costs. Inland sources provided by trucking would also have environmental impacts associated with the quarrying, transport, and placement of the sand. Estimates in the Monterey Bay area for truck delivered beach-quality sand in 2004 were around \$21/yd^3 (the offshore area in this location is a national marine sanctuary such that dredging sand from the seafloor

is not acceptable under existing policies). A recent proposal for a nourishment project in southern Monterey Bay estimated the total cost associated with delivering ~240,000 yd^3 of sand (to build a beach ~3,000 feet long and 100 feet wide) from an inland source would be ~$5.5 million dollars (~$23/yd^3).

It is also important to look objectively at the logistics of a nourishment project of this scale. Placing 240,000 yd^3 of sand on the beach would require 24,000 10-yd^3 dump truck loads of sand. If a dump truck could deliver a load of sand to the beach and dump it every 5 minutes, 96 truckloads could be dumped in an 8-hour day. Keeping this process going 7 days a week could deliver 2880 truckloads or 28,800 yd^3 each month. At this rate, it would take over 8 months to complete this nourishment project. There are still issues of delivering sand in the winter months when high wave conditions might make truck traffic on the beach difficult; placing sand in the winter months would also reduce the lifespan of the nourished sand. During the summer months there are beach users to deal with. While none of these are overwhelming obstacles, beach nourishment from inland sources by truck is not a simple or straightforward process.

Beach nourishment projects using terrestrial or inland sources of sand can be very expensive undertakings and any such project will probably have to be re-nourished on a regular basis unless the sand is somehow retained. The limitations and costs associated with beach nourishment and re-nourishment must be balanced by the ultimate benefits of the project, including the

recreational and economic value of widening a beach, in addition to the back-beach protection offered to development by a wider beach.

Nourishment History of Individual Littoral Cells

In California, beach nourishment (not including harbor bypassing) has historically provided on average ~1.3 million yd^3 annually to the beaches in southern California (Point Conception to the international border), representing 31% of the overall sand budgets in the area (Table 4.1). Large quantities of sand excavated during major coastal construction projects, such as the excavation associated with the Hyperion Sewage Treatment Facility (17.1 million yd^3 from 1938-1990) and Marina del Rey (~10 million yd^3 from 1960-1963) in the Santa Monica littoral cell, as well as the dredging of San Diego Bay (34 million yd^3 between 1941-1985) have provided millions of cubic yards of sand to the beaches of southern California (see comprehensive summary articles by Flick, 1993 and Wiegel, 1994 for detailed discussion of southern California beach nourishment projects.). Between 1942 and 1992 about 100 million yd^3 of material were placed on the beaches, with approximately half of the sand derived from harbor or marina projects (Flick, 1993).

Santa Monica Littoral Cell. In the Santa Monica littoral cell, over 29 million yd^3 of sand has been placed on the beaches since 1938 for projects where the primary objective was not beach nourishment. As a result, the shoreline in many areas of Santa Monica Bay has advanced seaward from 150 to 500 feet

from its earlier natural position. Although the majority of beach fill was placed prior to 1970, beaches in this area are still wider than their natural pre-nourished state, due, in large part, to the construction of retention structures to hold the sand in place. Currently, there are 5 harbor breakwaters, 3 jetties and 19 groins along the nearly 19 miles of shoreline from Topanga Canyon to Malaga Cove, effectively trapping the sand before it is lost into Redondo Submarine Canyon. Sand retention structures have been very effective at maintaining the wide artificial beaches in the Santa Monica littoral cell because of the nearly unidirectional longshore transport to the southeast.

San Pedro Littoral Cell. In the San Pedro littoral cell, federal, state and local governments fund ongoing beach nourishment at Sunset Beach (just downcoast of Seal Beach) to maintain a wide enough beach to meet the recreational demands of the area and to mitigate for the erosion caused by the construction of the Anaheim jetties. The area is nourished with ~390,000 yd^3 of sand annually. Herron (1980) stated that 22,000,000 yd^3 of sand from harbor and river projects had been placed on the 15 miles of public beaches of the San Pedro littoral cell.

Oceanside Littoral Cell. Nearly 9.3 yd^3 million of sand were been placed on the beaches of the Oceanside Cell between 1943 and 1993 (Flick, 1993). This represents an annual average rate of about 250,000 yd^3. Most of this sand has come from the dredging of Agua Hedionda Lagoon and Oceanside Harbor which

each contributed about 4 million yd^3 in 1954 and 1961 respectively. About 1,300,000 million yd^3 were trucked from the San Luis Rey River bed to the Oceanside beaches in 1982. Two smaller projects including the construction of the San Onofre Nuclear Power Plant and nourishment of Doheny Beach each generated about 1,300,000 million $yd^{3.}$

Mission Bay Littoral Cell. The beaches in the Mission Bay littoral cell have also benefited from large construction projects along the coastline. Nearly 4 million cubic yards of sand dredged from Mission Bay to create the aquatic park and small craft harbor were placed on the beaches to create wider recreational areas.

Silver Strand Littoral Cell. The Silver Strand littoral cell is somewhat unique in the region in having an overall net littoral transport from south to north. The nearly 35 million yd^3 of sand placed on its beaches since 1940 represents the most highly altered stretch of beach in southern California (Flick, 1993). Much of this volume, about 26 million yd^3, was excavated from the massive expansion of naval facilities in San Diego Bay just after WWII. Prior to this effort the Silver Strand had been a relatively narrow sand spit separating San Diego bay from the ocean, which was occasionally overwashed by storm waves.

San Diego Association of Governments (SANDAG) Project. The most recent large-scale, non-opportunistic beach nourishment project in California with the sole purpose of widening the beaches was completed in San

Diego County in 2001. Approximately 2-million yds^3 of sand were dredged from six offshore sites and placed on 12 beaches in northern San Diego County at a total cost of $17.5 million dollars or $8.75/$yd^3$ (Figure 5.3). 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 (Figures 5.3 & 5.4). Eighty-five percent of the sand went to the beaches of the Oceanside Littoral Cell. A comprehensive regional beach-profiling program had been in place since the 1983 El Niño event, which provided a baseline for monitoring the results or status of many of the individual nourished sites. Sixty-two beach profile lines were surveyed and most of these twice yearly, in the fall and the spring. Seventeen of these profile lines either already existed or were established at the individual beach nourishment sites (Coastal Frontiers, 2005).

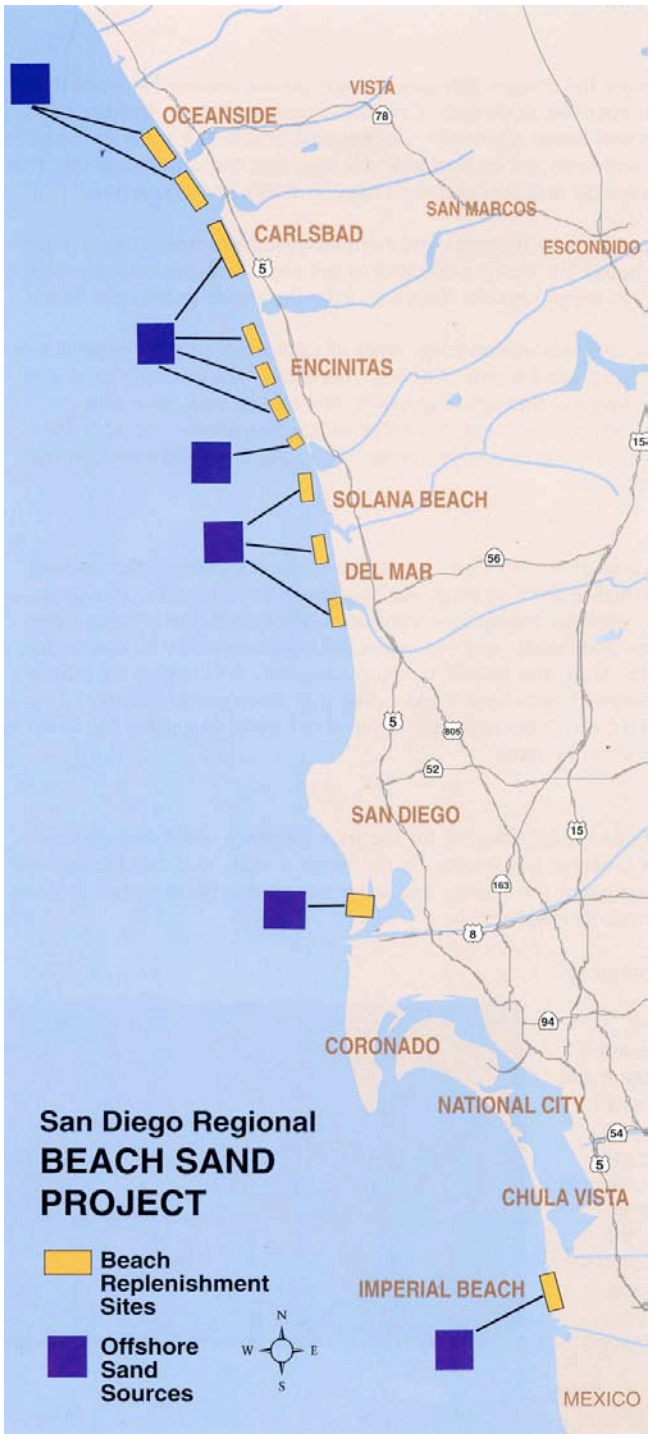

Figure 5.3. Offshore sand sources and nourishment sites for the 2001 SANDAG 2,000,000 yds^3 beach nourishment project.

Figure 5.4: Beach nourishment at South Carlsbad State Beach. In July 2001. 150,000 yds^3 of sand were placed on this beach in a fill that was 2000 feet long, 180 feet wide and up to + 12 feet msl.

While it is difficult to completely evaluate and summarize the vast amount of beach survey data that have been collected in this report, it is important to try and extract some overall measures of performance or behavior following the nourishment if we are to derive any useful conclusions from this large project.

At 14 of the 17 nourishment sites surveyed, the beach width (as determined by mean sea level shoreline position) narrowed significantly between the fall of 2001 (immediately following sand placement) and the fall of 2002. While the beaches that were surveyed showed initial increases in width of 25 to over 100 feet from the nourishment, most of these beaches narrowed by 20 to

60 feet during the first year following sand emplacement. Twelve of the 17 sites showed further decreases in width over year two, and 13 of these sites continued to decrease in width in the 3rd year. Three of the beaches in the Oceanside Cell showed modest width increases (6 to 15 feet) in the first year following nourishment, but in the two following years, all declined in width.

A very detailed study of the Torrey Pines State Beach fill was carried out as part of the post-nourishment monitoring (Seymour, et al. 2005). This fill was 500 meters long and included about 330,000 yds^3 of sand, one of the larger fills. Rather than being constructed as a sloping fill, the upper surface was level and terminated in a near-vertical scarp about 6 feet high. Bi-weekly profiles 65 feet apart were collected along 1.8 miles (9500 feet) of beach and extended offshore to a depth of 26 feet. The temporal and spatial resolution provided by this surveying program, in combination with offshore wave measurements, provided an exceptional database for documenting the relationship between wave conditions and the behavior of a beach fill (Seymour, et. al., 2005).

The fill was completed near the end of April, 2001 (Figure 5.5). Wave conditions during the summer and fall were mild, with significant wave heights (the average of the highest 1/3 of the waves) generally less than 3 feet except for a few incidents of waves as high as 5 feet. The front scarp of the fill remained intact and there were only modest losses at the ends of the fill.

Figure 5.5. Aerial view of the Torrey Pines beach fill project (from Seymour, et.al., 2005).

At noon on Thanksgiving Day, November 22, 2001, significant wave heights reached nearly 10 feet and remained in the range of 9 to 10.5 feet for seven hours. The fill was overtopped and began to erode quickly. By daylight on November 23, the fill had been almost completely eroded to the riprap at the back of the beach (Seymour, et al., 2005). The fill was stable for approximately 7 months of low wave energy conditions but was removed within a day when the first significant waves of the winter arrived.

Some overall conclusions can be drawn from the four years of published beach surveys in the nourished areas (Coastal Frontiers, 2005). The performance of the individual beach fills varied considerably. At some sites, such as Del Mar, Moonlight, and South Carlsbad, the gains in the *shorezone* (defined as the subaerial or exposed portion of the beach *as well as* the nearshore sand out to the seasonal depth of closure) that occurred during placement of fill were short-lived. At other sites, such as Mission Beach and Oceanside, the gains in the shorezone persisted through the time of the Fall 2004 survey. In many cases, dispersal of the fill was accompanied by shorezone volume gains on the downdrift beaches. Both the grain size of the sand and the volume of the fill were important factors in how long nourished sand remained on the beach. For the smaller fills, erosion or losses from the ends of the fills were significant. One very small nourishment site in the Oceanside cell (Fletcher Cove) received a small volume of very-fined grained sand and it was removed very quickly.

Nearly all of the sand added to the beaches in the SANDAG project tended to move both offshore and also alongshore with the arrival of winter waves although much of this has persisted just offshore in the shorezone. This sand does provide some benefits including dispersing some of storm wave energy and flattening the beach profile. However, most of the general public expects to see a wider exposed beach as the benefit of a beach nourishment project. It is important to understand for the SANDAG project or any nourishment plan or proposal, that most beaches have some normal or

equilibrium width, as discussed earlier. Without either regular or repeated nourishment, or the construction of a retention structure, such as a groin, to stabilize or hold a beach fill, there is no reason why in an area of significant longshore transport and moderate to large winter wave conditions, that the sand should stay on the exposed beach for any extended period of time. The considerations that need to be weighed prior to any beach nourishment project, are whether the benefits of littoral cell or shorezone sand increases, and the relatively short-term or temporary beach width increases resulting from beach nourishment are worth the initial investment and continuing costs.

Chapter 6: Conclusions:

Before large-scale human influence or interference, the majority of beaches in southern California were relatively narrow. Large coastal construction projects, the creation and expansion of harbors and marinas, and other coastal works found a convenient and cost-effective disposal site for excavated material on the beaches in southern California creating the wide sandy beaches that people have come to expect in this region, particularly along the beaches of the Santa Monica littoral cell and the Silver Strand cell. The majority of sand was placed before the mid-1960's, however. Since then, the rates of nourishment have dropped sharply. However, in many cases, sand retention structures such as groins were built in conjunction with the placement of beach-fill, which have been successful in stabilizing the sand and maintaining the wider beaches. Carefully designed retention structures have been shown to extend the life of beach nourishment projects, and should be considered when planning beach restoration projects in the future. Beach nourishment is not a permanent solution to problems associated with beach erosion, however.

When assessing the success or failure of a nourishment project, one must look beyond the individual beach where the nourishment took place and examine the regional effects throughout the entire littoral cell. Often the nourished site serves as a feeder beach, providing sand to be transported by littoral drift to "feed" or nourish the downdrift beaches. Without detention structures such as

groins, however, sand placed on a beach will move downcoast with the littoral drift. Where littoral drift rates have been documented they are typically in the range of about a mile-per-year (Bruun, 1954; Wiegel, 1964; Griggs and Johnson, 1976), although this will depend upon the wave energy, the orientation of the shoreline, and the angle of the dominant wave approach. Depending on the potential littoral drift in an area, nourishment projects may have a fairly short residence time on a particular beach. However, if well planned on a regional scale, the placed sand should feed the downdrift beaches until ultimately ending up in a submarine canyon, offshore, or retained behind a coastal engineering structure.

When engineering a beach nourishment project in California, it is important to consider such elements as grain size compatibility, fill density, or the volume of sand per unit length, possible sand retention structures and the effects on down drift beaches, the rate and direction of littoral drift, and wave climate (including storm duration and intensity).

While harbor maintenance and large construction projects along the coast may be excellent sources of opportunistic beach nourishment, there are many difficulties and possibly prohibitive limitations associated with nourishing the beach with sand taken from an inland or terrestrial source including the 80:20 rule, cost, financial responsibility of the project, the source and method for obtaining sand, transporting large quantities of sand to the nourishment site, and

the potential for covering over marine life or habitats when placing the sand. Offshore sand sources also have their limitations and impacts including costs, location of compatible sand offshore, permit issues such as environmental impacts associated with disturbing the seafloor habitat, transporting and placing large quantities of sand (Figure 5.4) increased turbidity, etc.

The limitations and costs associated with beach nourishment must be balanced by the ultimate benefits of the project including the economic and aesthetic value of widening a beach in addition to the back-beach or coastal protection offered by a wider beach.

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