Photo: Ryan Anderson, Wisconsin Street, Oceanside California 2019

An Evaluation of Sand Transport Rate and Direction(s) in the Oceanside Littoral Cell

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Executive Summary

- Decades of study of the northern Oceanside Littoral Cell confirm that littoral drift or longshore sediment transport along this stretch of coast generally moves to the south during the fall and winter months when waves from the northwest dominate, and to the north in the spring and summer months when southern hemisphere swells from the southwest dominate.

- In its natural state, the beaches of Oceanside were very wide and were nourished by sediment delivered by both rivers and creeks discharging upcoast as well as erosion of the uplifted terraces and coastal bluffs. Damming of significant portions of these watersheds beginning in 1922 gradually reduced the fluvial sediment supply to the coastline, which has now been decreased by ~154,000 yds^3/year or 54%.

- The initial construction of the Del Mar Boat Basin in 1942-43 led to the accumulation of sand upcoast of the harbor breakwater with the formation of a 400-500-foot-wide beach and then sand moving around the tip of the breakwater into the entrance channel and harbor. Littoral sand from the south was initially also transported into the harbor. Trapping of littoral drift by both the Marine Corps Del Mar Boat Basin and the public Oceanside Small Craft Harbor (built in 1963) led to the reduction of sand downcoast and eventually the virtual elimination of the historically wide sandy beaches of Oceanside.

- A significant extension of the upcoast Oceanside Harbor breakwater in 1958 led to the offshore deflection of littoral transport and the formation of a sand bar in water depths between 40 and 60 feet which extends at least five miles alongshore to the south. The total offshore deposition translates into an average annual accretion rate of ~144,000 yds^3/year if this transport dates to the initial construction of the Del Mar Boat Basin in 1942.

- Since harbor construction was begun in 1942, approximately 10.1 million yds^3 of sand have been placed on the Oceanside beaches from a combination of harbor construction and beach nourishment, with an additional 18 million yds^3 from Oceanside harbor dredging and sand bypassing. Very little of this sand has remained on the beaches for any significant period, however.

- There are several possible reasons why this added sand has not remained on the Oceanside beaches or why the beaches haven't returned to their pre-harbor widths. When development occurred along the shoreline beginning in the mid-1940s, homes and other structures appear to have been built on the back beach that extended 100-125 feet seaward or covered approximately 32 acres of beach that were permanently lost. Thus, much of the natural equilibrium beach was lost. Immediately downcoast of Aqua Hedionda Lagoon, there is a slight bulge in the coastline, that may have extended further seaward in the past and acted as a retention structure to trap littoral drift.

- An additional factor affecting the beach width is the continuing rise in sea level on a shoreline that is now nearly completely armored. The Oceanside shoreline should be experiencing *passive erosion* (Griggs, 2005), which will gradually flood or drown the beach. Over the past 100 years, when some of the original photos were taken showing a very wide beach, the closest tide gauge (at La Jolla) has recorded a sea-level rise rate of 2mm/year. Over 100 years, this sums to ~8 inches, which could have led to significant shoreline retreat for this low sloping beach.

- Since 1961, five different calculations or estimates have been made of the net annual longshore transport of sand to the south along the shoreline of the northern Oceanside Littoral Cell. Using nearshore or offshore wave data, potential littoral drift has been calculated which provides an estimate of the amount of sand that could be transported by the available wave energy if sand was available. These values range from about 102,000 to 254,000 yds^3/year. There are many sources of uncertainty in these calculations, however, and these rates vary from year to year depending upon wave conditions.

- Using 57 years of dredging volumes for the Oceanside Harbor complex produces an average annual net longshore sediment transport rate to the south of ~240,000 yds^3/year, which we believe is a reasonable best value for long-term littoral drift. The advantage of using the long history of dredging records as the proxy for littoral drift is that year to year variations as well as the PDO cycles will be averaged, and the long-term trends are evident.

- Many previous studies of the cell have estimated upcoast littoral drift in the spring and summer months on the order of 550,000 yds^3/yr. With the discharge of sediment dredged from the harbor on the downcoast beach, depending upon the time of year and placement site, it is highly likely that a significant portion of the average annual dredged volume of sand is carried back into the harbor entrance. Thus the ~240,000 yds^3/yr. may include a substantial amount of sand that is re-dredged, so the net downcoast littoral transport may be significantly less than 240,000 yds^3/yr.

- The average volume of sediment dredged from Aqua Hedionda Lagoon and deposited on the adjacent beaches is less than the upcoast average annual harbor dredging rates. However, dredging only takes place every two years and considering the narrow entrance channel (~200 feet), it is highly likely that a substantial portion of the littoral drift is transported across the entrance to downcoast beaches during ebb tides, during periods of large waves, or when the entrance is shallow, and is not a component of the dredged volume.

- An additional potential loss of sand at Agua Hedionda is offshore transport to the head of Carlsbad Submarine Canyon. While older reports concluded that the canyon head was no longer active, the most recent and detailed bathymetry indicates that the canyon head extends to a depth of 50 feet, which is within the depth range (40-60 ft.) of the sand bar that has formed from sand deflected offshore by the Oceanside Harbor breakwater.

Introduction to Littoral Drift and Littoral Cells

Sand is constantly in motion along California's shoreline under the influence of the waves. A longshore current develops parallel to the coast because of waves approaching the shoreline at an angle, breaking onshore, and retreating back down under the influence of gravity. This zigzag motion (Figure 1) of the water moves sand along the shoreline as well. Littoral drift refers to the movement of the sand grains in the direction of the longshore current, either upcoast or downcoast, depending on the angle of wave approach. Longshore transport for a stretch of coast will typically be a combination of both upcoast and downcoast transport, typically depending on the seasonal trends of wave approach. For any stretch of coastline, gross littoral drift is the total volume of sand moving (both upcoast and downcoast) under the influence of the waves while the net littoral drift is the difference between the two volumes (upcoast and downcoast). For example, there may be ~200,000 cubic yards of sand moving downcoast during the winter months and ~50,000 cubic yards of sand moving upcoast during the summer months. Thus, the gross littoral drift for that given year would be ~250,000 cubic yards of sand and the net littoral drift would ~150,000 cubic yards downcoast.

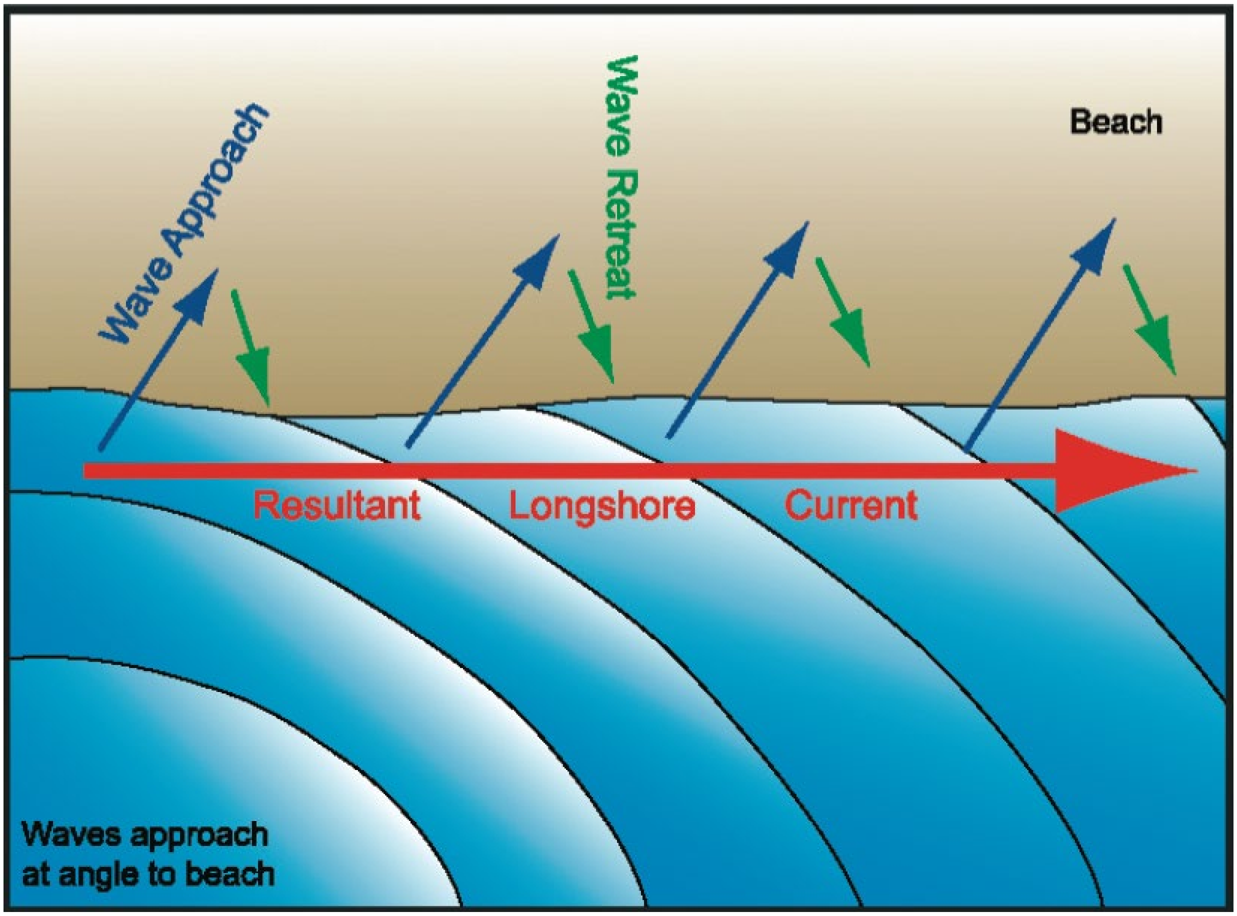

Figure 1: Development of longshore current due to waves approaching the beach at an angle. Littoral drift refers to the net movement of sand grains in the direction of the longshore current.

Many years of study of the coastline of southern California led to the recognition of a series of distinct beach compartments or littoral cells (Inman and Frautschy,1966). These are self-contained segments of the coast characterized by distinct sources of sand, littoral drift or longshore transport, and sinks, or routes where the sand is lost from the cell. It was the discovery of the many offshore submarine canyons along the southern California coast and the realization that sand moving downcoast along the beaches was flowing into these canyons that initially led scientists to this concept. Downdrift of many of the canyons, the beaches narrow or disappear and rocky headlands or points typically mark the end of each compartment or littoral cell. Continuing downdrift, streams again begin to deliver sand to the shoreline, bluffs erode adding more sand, and beaches appear. As more sand enters the cell, the beaches continue to widen downcoast. Beach sand is also conveyed onshore or offshore along the entirety of the littoral cell often in response to seasonal changes in wave energy. The offshore continental shelf can be a potential source of sand when large waves transport sand onshore, or a sink, when flood discharge of large rivers can move sand offshore. These contributions or losses are particularly challenging to quantify, however, due to the combination of the large areas of shelf involved and documenting the actual changes in the thickness or amount of sediment that may occur during these episodic events.

Adding sand to beaches through artificial nourishment constitutes a large source of sand to southern California beaches. Between 1930 and 1993, over 130 million yds^3 of sand were added to the beaches of southern California (Flick, 1993; Wiegel, 1994). Initially, this sand came primarily from dredging of existing harbors, new marinas, and river channels, and from construction projects in coastal dunes.

Some distance downdrift, sand may be blown inland into dunes, and another submarine canyon may intersect the shoreline effectively removing sand from this system, and the end of another beach compartment or littoral cell is reached. These sources and sinks of sand form the framework for a sand budget in a littoral cell (Figure 2). If the sources of sand are greater than the sinks of sand, the beaches will grow or accrete. If the sources of sand are equal to the sinks of sand, the beaches in the littoral cell are likely in equilibrium, and if the sources of sand are less than sinks of sand, the beaches will erode.

Along the southern California coast, between Point Conception and La Jolla, five distinct littoral cells have been recognized: the Santa Barbara Cell, the Zuma Cell, the Santa Monica Cell, the San Pedro Cell, and the Oceanside Cell (Figure 3; Inman and Frautschy,1966). Each is characterized by individual sources of beach sand (primarily streams and bluff erosion), alongshore littoral drift, and a sink or sinks (coastal dunes and submarine canyons primarily). Other littoral cells have been recognized along the entire length of the California coast, although the boundaries and the total volumes of sand moving through these cells are still being measured and documented (Patsch and Griggs, 2006 a & b). Although distinct boundaries have been placed at the borders of littoral cells, typically at active submarine canyons, it also is clear that these boundaries can be leaky and that sand may move around or across canyon heads or around prominent headlands, for example, and transport sand between cells (Griggs & Patsch, 2018; George et. al, 2018).

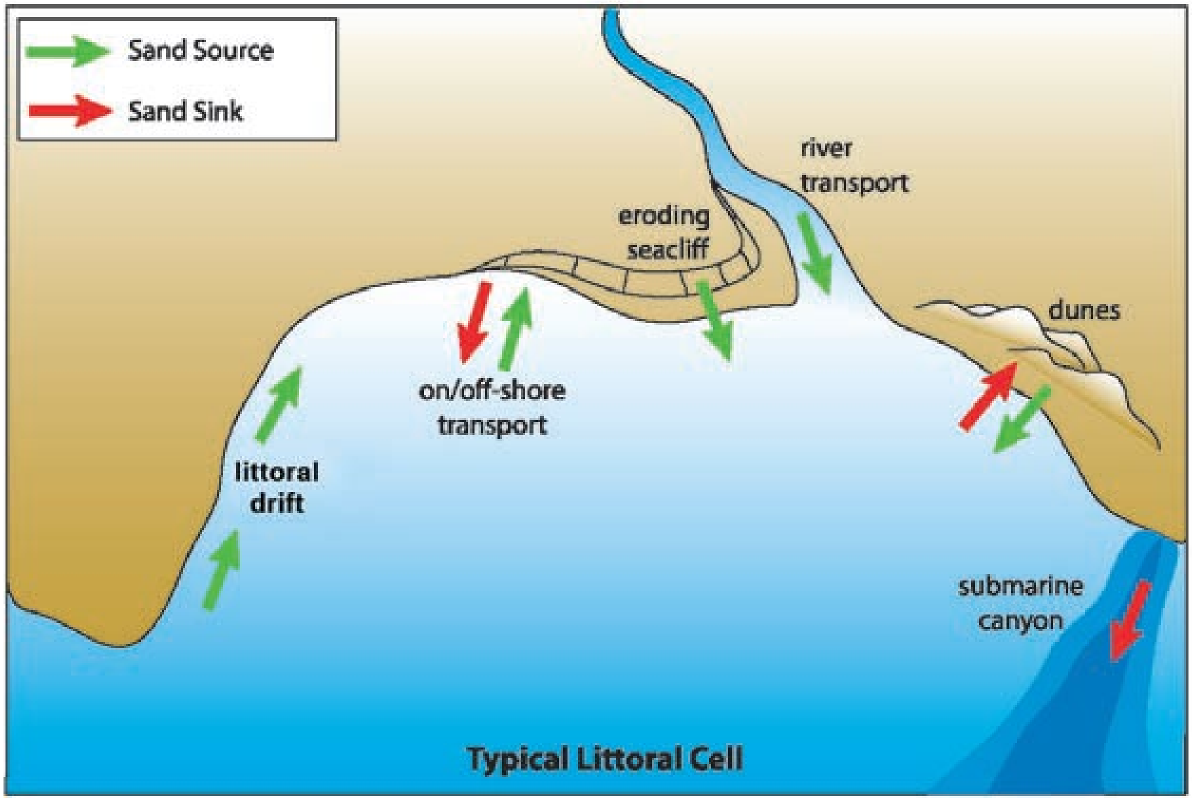

Figure 2: Sources and sinks of sand in an idealized Littoral Cell

Figure 3: Littoral cells of the Southern California coast.

Quantifying the Individual Components of Littoral Cell Sand Budgets

Considerable research has been and continues to be undertaken to quantify and understand the individual components of littoral cell sand budgets, specifically: 1) the amount of beach compatible sand contributed by individual streams and specific sections of eroding coastal bluffs or cliffs; 2) the directions and rates of longshore sand transport or littoral drift; and 3) the amount of sand lost to different sinks such as submarine canyons or coastal dunes. While California's littoral cells were first recognized nearly 60 years ago (Inman and Frautschy, 1966), the development of detailed budgets for individual cells has been challenging and still involves many uncertainties in quantifying the sand delivery to the shoreline, rate of movement along the shoreline, and losses from individual cells (Patsch and Griggs, 2006a & b).

Not only are these budget components difficult to quantify, but there is also significant variability in individual components over time. Streams contribute the overwhelming majority of sand to California's beaches (~71% on a statewide basis), but the fluvial transport of sand (which is carried as both bedload and suspended load) is both difficult to measure accurately and extremely episodic, even within a single year (Griggs, 1987; Brownlie and Taylor, 1981). There are also significant differences in fluvial sand delivery between El Niño and La Niña years (Inman and Jenkins, 1999; Warrick and Milliman 2003; Warrick, 2020). Some researchers believe that the values reported for annual delivery of sand by streams should be considered as plus or minus 30% or more (Brownlie and Taylor, 1981; Willis and Griggs, 2003).

Both the natural sources of littoral sand and the rates of littoral drift can and have been altered along the coast of southern California by several anthropogenic impacts. These include dams and debris basins in watersheds, which trap sediment that would have otherwise been discharged to the shoreline and entered the littoral drift system. There are many of these types of structures in the watersheds of southern California that have significantly reduced sediment flow to the coast (Brownlie and Taylor, 1981; Willis and Griggs, 2003; Slagel and Griggs, 2008). Coastal protection structures (primarily seawalls and rock revetment, but also breakwaters) eliminate or lower the erosion rates of cliffs, bluffs, and dunes, thereby reducing the amount of sediment that would have ended up on the shoreline. For the 233 miles of California's four southern counties (San Diego, Orange, Los Angeles, and Ventura) shoreline, 88.2 miles or 37.8% has now been armored (Griggs and Patsch, 2019). Large coastal engineering structures such as groins, jetties, and breakwaters have also played important roles in impacting littoral sand transport and its storage or, in some cases, diverting this offshore.

The amount of sand contributed by eroding coastal bluffs is also an episodic process. This can vary over time as a function of storm frequency and intensity as well as tidal elevations. Contributions from bluff retreat can also vary significantly alongshore, depending upon the materials making up the bluff, the average rate of bluff retreat, the height of the bluff, and the percentage of sediment larger than the littoral cut-off diameter (Limber, Patsch, and Griggs, 2007). Because of the temporal variations in sand contributions from both fluvial sources and bluff retreat, the number of years of record or observations is important in affecting the reliability of the average annual input values obtained. With a warming climate, rainfall, runoff, wave climate, and sea level will continue to change, which over time will progressively alter the processes delivering sand to the shoreline and transporting it alongshore.

Determining Rates of Littoral Drift or Longshore Transport

The rate of longshore transport of sand or littoral drift along the shoreline has been difficult to determine with a high degree of confidence for the reasons discussed above. Nonetheless, several different methods have been used and are outlined below.

Potential Littoral Drift

Calculating potential littoral drift rates mathematically involves several factors such as wave energy, direction, and period, sediment size and shape, beach slope, and wind direction and complex modeling. While *potential littoral drift* rates have been calculated from offshore wave data, these values are extremely sensitive to nearshore bathymetry, and will vary widely depending upon the actual wave data used (whether deep or shallow water, and the time-period used) and the location where the data were recorded (Inman, 1976; Hales, 1978; Tekmarine/ACOE, 1987; Inman & Masters, 1991). In addition, the rates calculated are a measure of the amount of sand that could be transported, hence *potential,* if that sand were available. Along the coastline of southern California (the Southern California Bight, extending from Pt. Conception to the Mexican border), the *shadowing effect* of the offshore Channel Islands exerts a significant effect on wave energy and direction that reaches individual segments of the shoreline, which affects both direction and rate of littoral drift. In practice, littoral drift rates are more typically estimated using a combination of numerical models, empirical data, and field observations used as proxies of littoral drift rate (accumulation of sediment upcoast of a shore perpendicular structure, rates of harbor dredging, etc.).

Rates of Beach Accretion Updrift of a Littoral Barrier

The rate of sand accumulation behind or updrift of a large engineering structure such as a groin, jetty, or breakwater immediately following completion provide a good measure of littoral drift over a short time-period until littoral drift begins to pass around the structure (Figure 4) or fill the entrance channel if stabilizing a harbor entrance. Good examples would be the Santa Barbara breakwater, the Redondo King Harbor breakwater, and the jetties at the Santa Cruz Small Craft Harbor (Griggs and Johnson, 1976). To be able to document the rates of accumulation, however, accurate pre-construction topographic and bathymetric surveys are needed, followed by detailed annual surveys. While historical aerial photographs usually exist to provide a qualitative record of sand accretion, to our knowledge, detailed and regular post-construction topographic and bathymetric surveys do not exist for most harbors, and typically littoral drift may partially bypass an engineering structure within a few years or sooner (Griggs and Johnson, 1976).

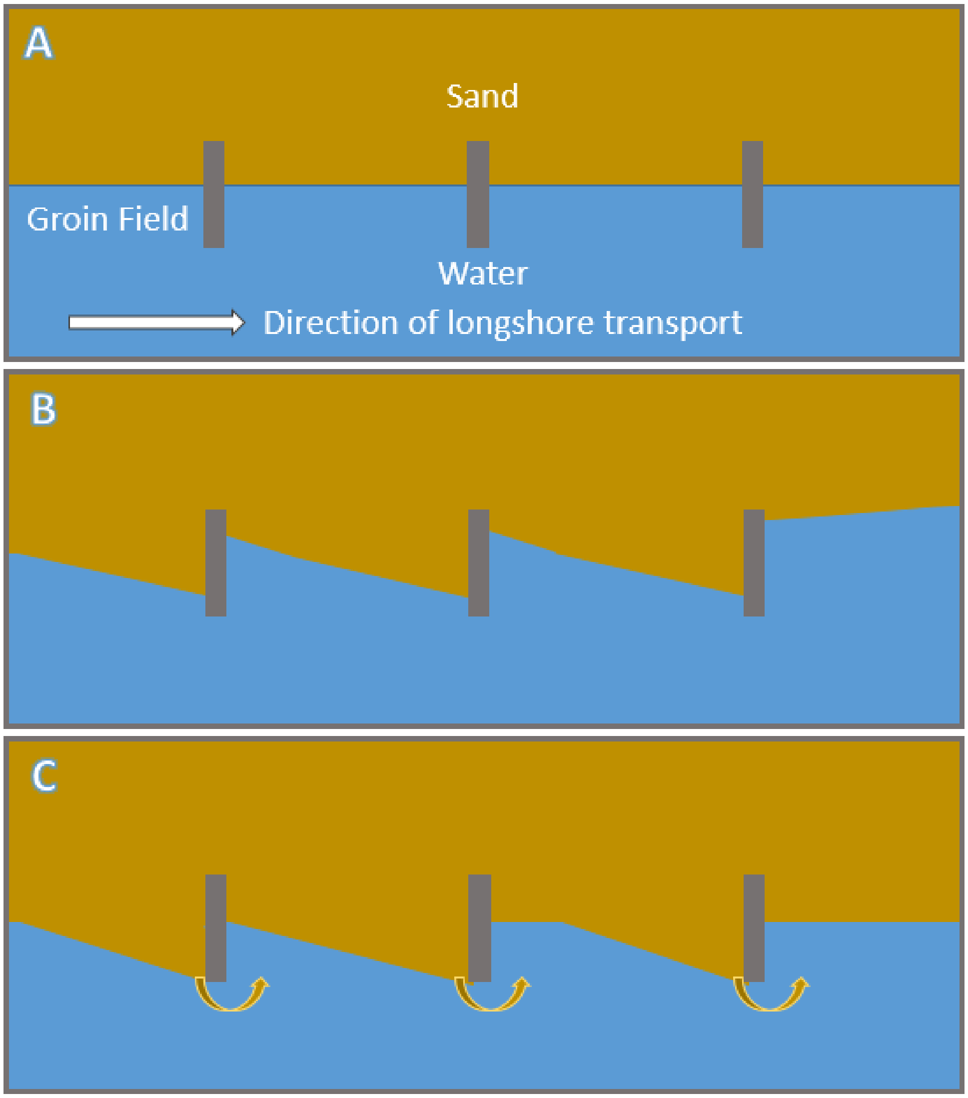

Figure 4: A. Groin field constructed perpendicular to the beach with the intention to retain sand. B. With a net littoral drift direction to the right in the diagram, sand accumulates on the updrift side of the structure causing the beach to accrete and may erode the beach on the downdrift side of the structure depending upon groin length and spacing. C. Once the groin is charged, or reaches its capacity to interrupt littoral drift, sand will bypass the groin and once again provide sand to the downdrift beaches.

Rates of Transport into Submarine Canyons

Several efforts have been undertaken to document the volume of sand lost to southern California's submarine canyons, notably Everts and Eldon (2005; Figure 5). This process is also episodic and perhaps the most difficult to quantify simply because of the extreme difficulty in attempting to try and measure sand moving underwater into an offshore canyon head.

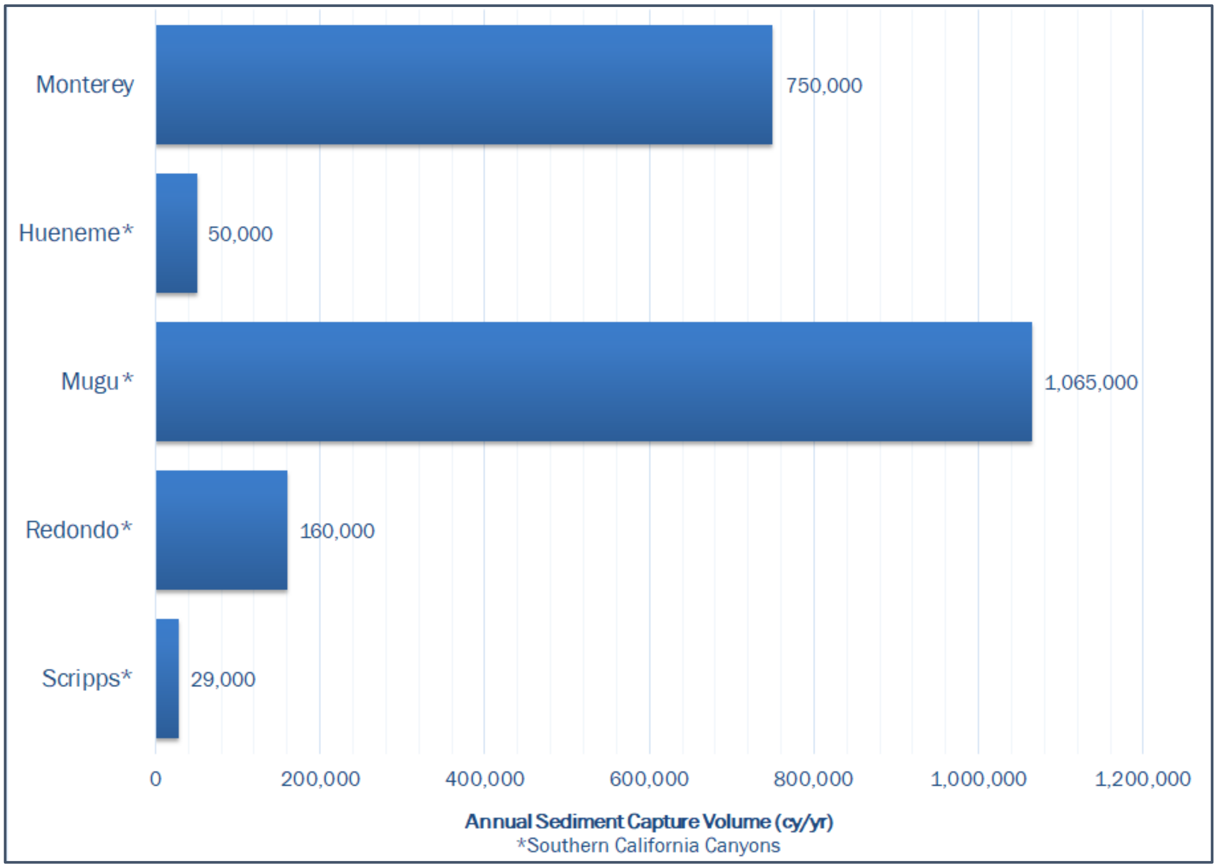

Figure 5: Approximate annual sand capture for submarine canyons funneling more than 10,000 cubic yards of sand per year offshore (Patsch and Griggs 2025; Moffatt & Nichol and Everts Coastal 2009; Everts Coastal 2002; and Everts and Eldon 2005). Figure from Griggs et al. 2020.

Harbor Dredging Rates

Patsch and Griggs (2006a & b) used harbor dredging rates as reasonable proxies for littoral drift rates for California's major littoral cells with harbors. Many of these harbors, Santa Cruz, Santa Barbara, Ventura, and Channel Islands, for example, form nearly complete littoral traps such that long-term average annual dredging rates are believed to be good estimates of net littoral drift at specific locations within cells. Average long-term harbor dredging rates can, therefore, be used as checkpoints for littoral drift rates at those locations within cells (Patsch and Griggs, 2021; Patsch and Griggs, 2019).

Balancing Littoral Cell Sand Budgets

Being able to quantify all of the average annual inputs of sand to a littoral cell reasonably accurately would theoretically allow you to develop a rough approximation of the annual volume or rate of sand transport alongshore. As discussed above, however, because of the overall challenges in quantifying littoral sand input from stream discharge or bluff failure, combined with both the temporal and spatial variability of these processes, makes this approach fraught with uncertainties.

The Oceanside Littoral Cell – Sand Budget and Littoral Drift Directions and Rates

The Oceanside Littoral Cell spans southern Orange and northern San Diego counties and extends approximately fifty miles, from Dana Point in the north to the Scripps-La Jolla submarine canyons in the south (Figure 6). Under natural unaltered conditions, "*the wide sandy beaches of Oceanside*" was an often-repeated phase to describe this stretch of coast and the shoreline in the Oceanside area.

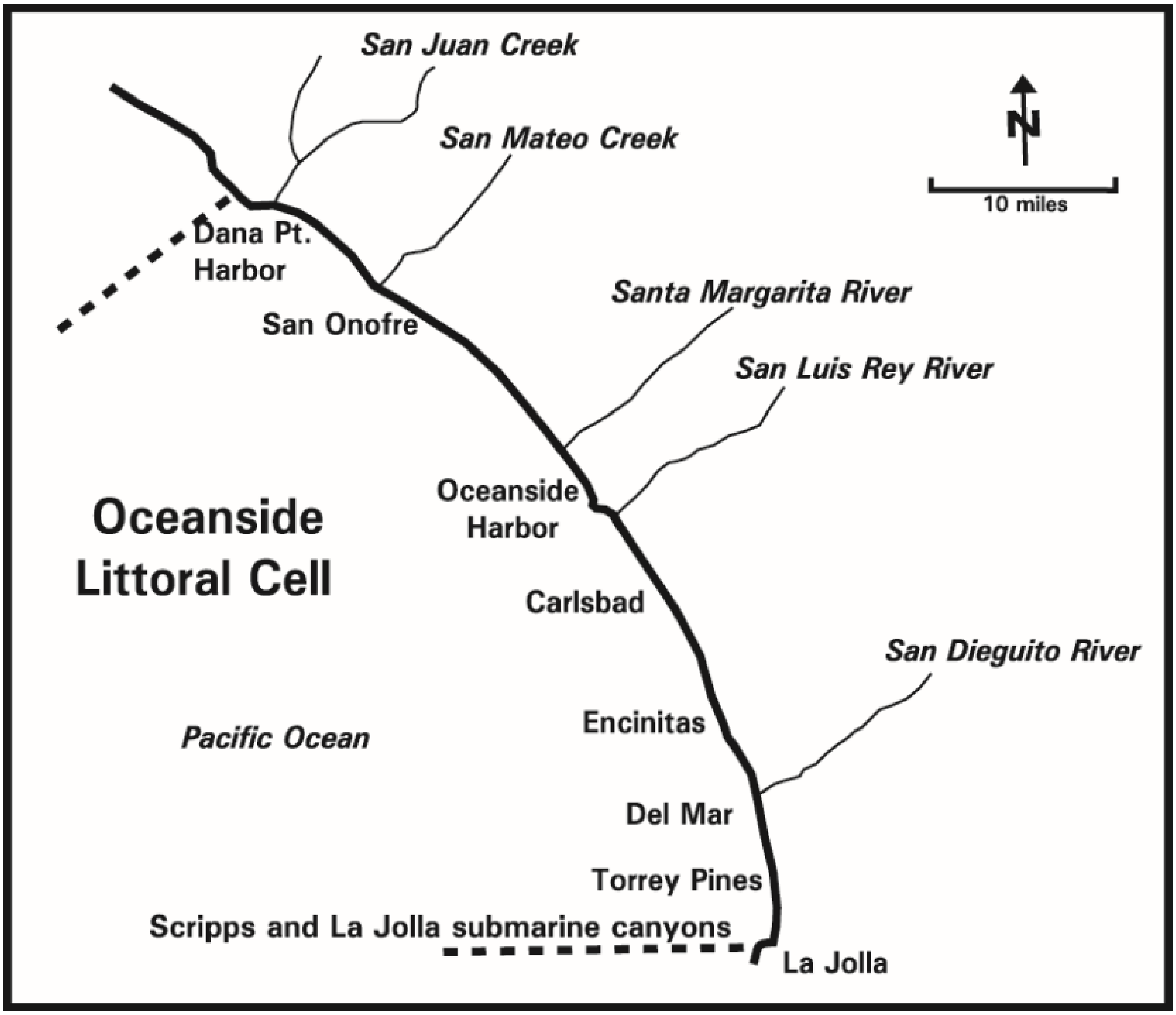

Figure 6: The Oceanside Littoral Cell extends from Dana Point to Scripps-La Jolla submarine canyons.

Anecdotal accounts suggest that prior to 1900 the beaches of the Oceanside Littoral Cell served as the most widely used "highway" along the coast (Chenault, 2007; Kuhn and Shepard, 1984). In the 1880s the U.S. Coast and Geodetic Survey noted that from the Torrey Pines area *"… there is an unbroken sand beach for forty or fifty miles or as far north of the valley of San Juan Capistrano…"* and the beach off Oceanside was approximately 300 feet wide (United

States Coast and Geodetic Survey, 1889; Kuhn and Shepard, 1984). A number of ground photographs covering the period from the late 1800s to the mid-1900s support these statements regarding the wide sandy beaches (Figures 7, 8, 9).

Figure 7: Construction of second pier at Oceanside (1894 - Note wide sandy beach).

Figure 8: Tent/Cottage City at Oceanside ~1927-1930 showing wide sandy beach south of the pier.

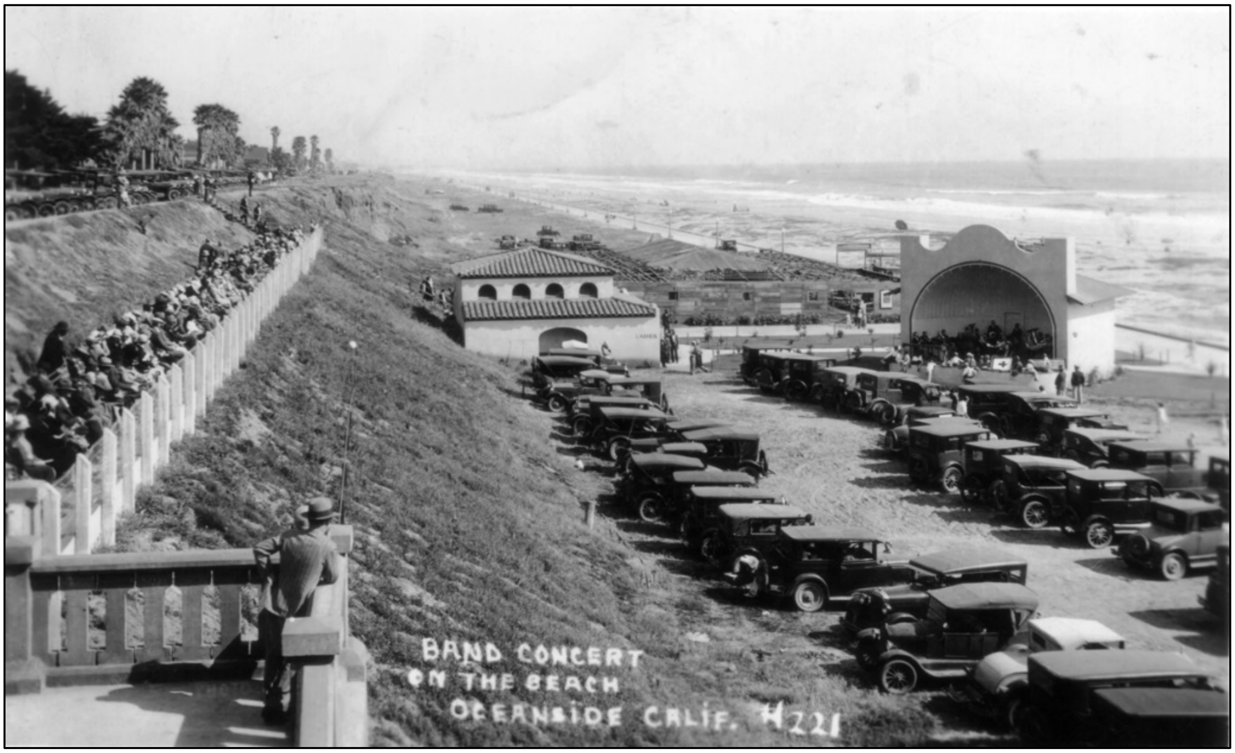

Figure 9: Bandshell and parking on the beach at Oceanside ~1937. Note wide sandy beach with low dunes and vegetation on the back beach.

Beach width and the direction and rate of littoral drift or the longshore transport of sand along the beaches of the Oceanside littoral cell is determined primarily by the amount of wave energy reaching the shoreline, the direction of wave approach relative to the orientation of the shoreline and the offshore bathymetry, and the amount of beach compatible sand that is available to transport. As discussed earlier, the primary sources of sand for this stretch of coastline are 1] coastal rivers and streams, and 2] cliff or bluff retreat. Both of these have been altered by human activity (Patsch and Griggs, 2006 a & b).

Reduction of Fluvial Sand Supply to the Shoreline from Dams and Reservoirs

The major fluvial or stream sources of sand for the northern Oceanside littoral cell are San Juan Creek and the Santa Margarita, San Luis Rey, and San Dieguito rivers. The San Dieguito River reaches the shoreline at Del Mar so is downcoast beyond the geographic scope of this report. Sand yields (both bed load and suspended load coarser than 0.63mm) were estimated by Willis and Griggs (2003) and Slagel and Griggs (2008) and are summarized in Table 1: Summary of sand-sized sediment yields for rivers and creeks in the Oceanside Littoral Cell. Sand transport to the coast from these rivers is highly episodic as a function of rainfall duration and intensity. Wiegel (1994) cites a report by Tekmarine (1987), stating that the last time the Santa Margarita and San Luis Rey River mouths were sufficiently breached as to allow a significant volume of sand to be transported into the littoral zone was in 1969 (the previous period of significant sand transport was in 1941; Patsch and Griggs, 2006 b).

Table 1: Summary of sand-sized sediment yields for rivers and creeks in the Oceanside Littoral Cell

River	**Source**	**Pre-Dam Sediment Load** *(cubic yards/year)*	**Post-Dam Sediment Load** *(cubic yards/year)*	**Percent Reduction**
San Juan	Willis and Griggs (2003)	40,000	n/a	n/a
Santa Margarita	Willis and Griggs (2003)	40,000	12,400	31%
	Slagel and Griggs (2008)	62,000	19,000	31%
	Average	**51,000**	**15,700**	**31%**
San Luis Rey	Willis and Griggs (2003)	40,000	27,600	69%
	Slagel and Griggs (2008)	66,000	20,000	30%
	Average	**53,000**	**23,800**	**45%**
San Dieguito	Willis and Griggs (2003)	12,500	9,875	79%
	Slagel and Griggs (2008)	5,000	2,000	40%
	Average	**8,750**	**5,938**	**68%**

In 1922 the Henshaw Reservoir was constructed on the San Luis Rey River. This structure reduced the sediment-carrying capacity of the river, thereby diminishing the natural supply of beach material to the Oceanside beaches. In 1949, Vail Dam on the Santa Margarita River, upcoast of the Del Mar Boat Basin, was built. However, any sand provided by this river can still reach the entrance channel to Oceanside Harbor to nourish Oceanside beaches.

The Santa Margarita and San Luis Rey rivers have had their natural sand yields reduced by an average of 31% and 45% respectively, (a total reduction of ~154000 yd^3/yr.) through damming (Table 1; Willis and Griggs, 2003; Slagel and Griggs, 2008). In the perspective of the entire Oceanside Littoral Cell, fluvial sources originally provided ~66% of the sand, and post-damming, the rivers now provide only ~33% of sand to the overall littoral cell budget, or 133,000 yd^3/yr. With bluff and terrace erosion providing the remainder (Table 2; Patsch and Griggs, 2006 a & b).

Oceanside Littoral Cell Budget

Inputs	Natural Supply of sand *cubic yards per year*	Actual Supply of Sand *cubic yards per year*	Reduction *cubic yards per year*
Rivers	286,500 (66%)	132,500 (33%)	-154,000 (54%)
Bluff Erosion	118,000 (27%)	100,000 (25%)	-18,000 (15%)
Gully/Terrace Erosion	31,500 (7%)	31500 (7%)	0
Beach Nourishment	n/a	138,000 (34%)	+138,000 (0%)
Total Littoral Sand Input	435,700 (100%)	401,700 (100%)	-34,000 (8%)

Table 2: Overall sand contributions and reductions to the Oceanside littoral cell. Reductions are due to the damming of rivers and the armoring of seacliffs. "Natural" sand yield refers to the estimated original volume of sand discharged by streams and contributed to the littoral budget through seacliff or bluff erosion. "Actual" sand yield refers to the estimated volume of sand reaching the coast under present day conditions considering reductions in sand supply from dams and seacliff armoring as well as additions to the budget from beach nourishment. From: Patsch and Griggs (2006 a & b).

Changes in Sand Contributions to the Shoreline from Bluff and Cliff Erosion

Approximately seventy-three percent of the Oceanside littoral cell consists of eroding seacliffs that range in height from 25 to 100 feet with the notable exception of the Torrey Pines area where cliffs reach heights of over 300 feet (Runyan and Griggs, 2002). At most locations, the seacliffs consist of two units: relatively resistant Eocene bedrock, composed of a variety of sedimentary rocks ranging from mudstone to sandstone and conglomerate, and a capping unit of unconsolidated Pleistocene terrace material. Once eroded, the bedrock and terrace deposits provide a wide range of grain sizes to the shoreline. By analyzing the grain size distribution of sand on nine beaches in the Oceanside Cell, the littoral cut-off diameter (Limber, Patsch, and Griggs, 2007) was determined to be approximately 0.088 mm (3.5Ø). Annual cliff erosion rates in this littoral cell, determined by Benumof and Griggs (1999) and Moore et al. (1998) and expressed as weighted averages for distinct segments of the cell, vary from ~0.4 to about 8 inches per year depending on the bedrock type, rock strength and structural weaknesses, wave climate, and terrestrial processes.

Using the littoral cut-off diameter of 0.088 mm, Runyan and Griggs (2002) determined from a grain size analysis of samples collected from the cliff bedrock and terrace deposits of the Oceanside Cell that these units contain, on average, about 51% and 57% respectively, of littoral-size material which contributes directly to the coastal beaches. Using the area of eroding cliff (linear extent and height or thickness of both the bedrock and terrace deposits taken from field measurements), multiplying this by the average percentage of littoral-size material in each geologic unit, and the average annual erosion rates calculated by Benumof and Griggs (1999) and Moore et al. (1998), Runyan and Griggs (2002) determined that the "natural" cliff contribution of sand to the beaches of the Oceanside cell (without taking into account the reduction of sand due to armoring structures) was approximately 67,300 yd^3/yr.

About twenty percent of the seacliffs in the Oceanside cell have some sort of protective armoring. Assuming the armor is 100% efficient at preventing seacliff erosion, armoring prevents approximately 12,400 yd^3/yr., or 18%, of the “natural” cliff contribution of sand-size material from entering the littoral cell (Runyan and Griggs, 2002). Thus, the work of Runyan and Griggs, using the erosion rates developed by Benumof and Griggs (1999) concluded that about 55,000 yd^3/yr. of littoral sized sand is presently being contributed to the beaches of the entire Oceanside cell from cliff and bluff retreat (Table 2).

In 2006, Young and Ashford re-evaluated the contributions of the seacliff and gully erosion to the beach sand budget in the Oceanside cell using airborne LiDAR (Light Detection and Ranging). Seacliff and gully/terrace beach sediment contributions were compared to coastal stream sediment contributions from previous studies. This study took place over a relatively dry 6-year period, however, extending from April 1998 to April 2004. The results indicate seacliffs of the Oceanside littoral cell provided about 100,000 yd^3/yr. of littoral-sized sand to the shoreline, almost twice as much as the earlier and less site-specific work of Runyan and Griggs (2002) and earlier values determined by Everts (1990) of 41,600 yd^3/yr.

Young and Ashford also reexamined the previous reports on littoral sediment contributions from gully erosion and terrace degradation used in earlier littoral budgets. Gullies yielded 26,000 yd^3 of sand annually during the six-year study period, which is significantly lower than the rates reported by Robinson (1988) and used in previous budgets. Robinson’s study covered a time period during which several severe gully events occurred as a result of altered drainage patterns associated with construction of the coastal highway. The gully erosion measured by Young and Ashford (2006), therefore, did not compare to the large gully events included in the Robinson study.

Patsch and Griggs (2006 b) used the more recent and site-specific work reported in Young and Ashford (2006) in their Oceanside Littoral Cell budget (Table 2). Comparison of their results to previous studies suggests that the relative seacliff sediment contributions may be significantly higher than previously thought (25% of the present-day littoral budget). Again, beach sediment contributions from gullies and terrace erosion were significantly lower compared with previous studies. This may in part be due to the episodic nature of gullying and the relatively dry study period used by Young and Ashford.

Harbor Construction and Beach Nourishment

Construction began on the Oceanside Harbor in 1942 with the development of the U.S. Marine Corps’ Del Mar Boat Basin. In 1958, its breakwater was extended, and in 1962 the adjacent Oceanside Small Craft Harbor facility was completed, along with another extension of the breakwater (Figure 10). Oceanside Harbor has required routine maintenance dredging since 1963 (Figure 11). Disposal of dredged material has been used to mitigate the erosion of the downdrift beaches resulting from the construction of the harbor. From 1958-2002 (64 years), ~18,700,000 cubic yards of sediment have been placed downdrift of Oceanside Harbor, averaging ~300,000 cubic yards of sediment annually (Table 3). This volume includes the 3.6 million cubic yards of material resulting from harbor deepening in 1963. If that volume is removed and the average of 57 years of consistent dredging is used (1965-2022), the total volume of material is ~13,700,000 cubic yards or ~241,000 cubic yards annually (Table 3)

In addition to the sand provided by the dredging of Oceanside Harbor, sand was added to the littoral budget in the Oceanside cell from the dredging of Agua Hedionda Lagoon (~4 million yd^3). Smaller projects such as the construction of the San Onofre Nuclear Generating Station (approximately 15 miles upcoast of Oceanside Harbor) from 1964-1985, provided an additional ~1.1 million yd^3 of sand to the beaches (Flick, 1989; Wiegel, 1994). Doheny Beach State Park, located updrift of Oceanside Harbor, was nourished in two increments with sand obtained from San Juan Creek (at the far northern end of the littoral cell immediately south of Dana Point Harbor) and from local marine terrace deposits (Wiegel, 1994). The downdrift portion of the beach, located 4,500 feet from San Juan Creek, was nourished with 690,000 yd^3 of sand trucked in from old terrace deposits at Camp Pendleton in 1966 (Shaw, 1980; USA/CESPL, 1965; Wiegel, 1994).

Figure 10:Sept. 8, 1963, photograph of Del Mar Boat Basin and Oceanside Harbor

The second part of the nourishment project took place on the beaches between Dana Point Harbor's east breakwater and the jetty on the north side of San Juan Creek. The terrace deposits added to the shoreline from each of these projects are not all beach compatible sand, however, so these volumes are overestimates. Runyan and Griggs (2002) carried out grain size analysis of marine terrace deposits in the Oceanside cell and determined that they averaged only 57% beach-sized sand. So, it is likely that only a little over half of these projects consisted of beach sized sand.

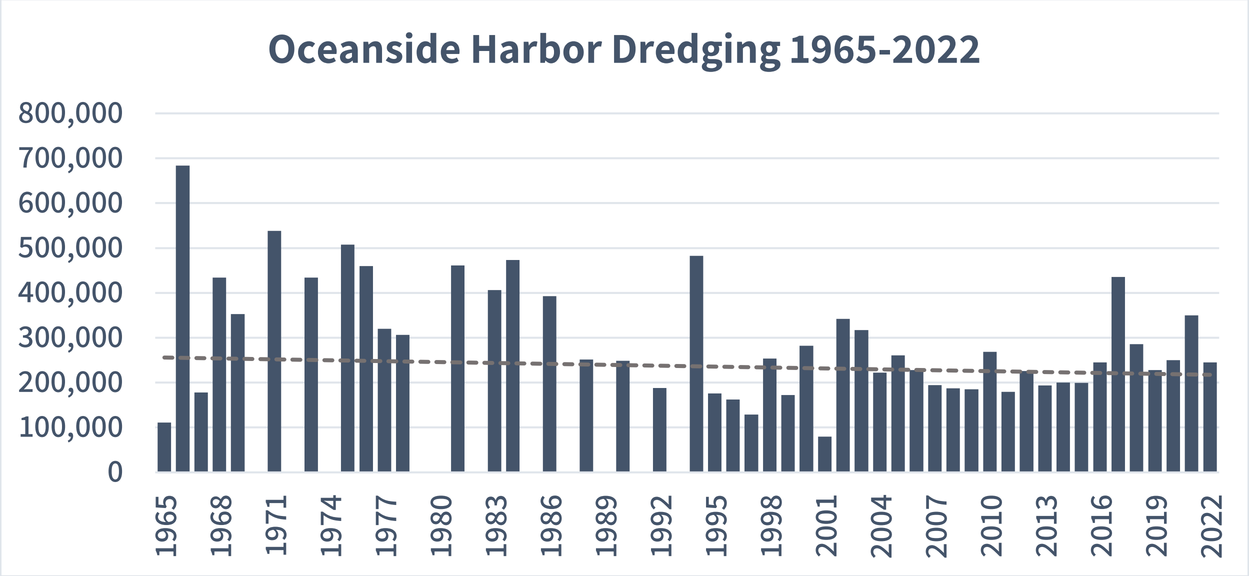

Figure 11: Oceanside Harbor dredging volumes in cubic yards from 196 to-2022.

Range	Number of Years	Total Volume Dredged (cy/yr)	Average Volume Dredged (cy/yr)	Comments
1958-2002	64	18,668,365	291,693	All years of Dredge Activity including 3.6 million cubic yards dredged for deepening in 1963
1965-2022	57	13,729,199	240,863	Not including the deepening of the harbor in 1963
2000-2022	22	5,606,024	254,819	Last 22 years
2010-2022	12	3,307,030	275,586	Last 12 years

Table 3: Summary of dredged volumes from Oceanside Harbor

In 1964, 94,000 yd^3 of sand, obtained from San Juan Creek was placed on the beaches (Wiegel, 1994). To maintain the fill, a groin was built on the north side of the mouth of San Juan Creek. This project formed a pocket beach 1,400-feet-long, which is still heavily used today, and changed the cobble beach to a sandy beach (Wiegel, 1994).

In 1982, 1.3 million yd^3 of sand were trucked in from the San Luis Rey riverbed to nourish the severely eroding beaches at Oceanside (Flick, 1994; Wiegel,1994). In total, beach nourishment (excluding bypassing/dredging from Oceanside Harbor) from 1940 to 2000 provided ~7.2 million yd^3 of fill on the beaches in this cell, which averages out to ~138,000 yd^3/yr. over the last 65 years (Table 2;Table 4).

Since 2000, approximately two million yd^3 of additional sand were dredged from six offshore sites and placed on the beaches of San Diego County at a cost of $17.5 million or $8.75/ yd^3 (RBSP I – Regional Beach Sand Project I; Patsch and Griggs, 2006). It was seen as an initial step in overcoming what had been perceived as a severe sand deficit on the region's beaches following the initial construction of the Oceanside Harbor. A total of six miles of beaches were nourished from Oceanside on the north to Imperial Beach on the south. About eighty-five percent of the sand (1,780,000 yds^3) went to the beaches of the Oceanside Littoral Cell. Nearly all the sand added to the beaches in the RSBP I tended to move both offshore and down coast with the arrival of winter waves (Griggs and Kinsman, 2016). Much of the sand in this nourishment project was placed at the northern end of the Oceanside Cell because of the anticipation of southerly transport, so losses to downcoast areas were not unexpected.

Eleven years after the first SANDAG nourishment project, in December 2012 RBSP II added an additional 1.5 million yds^3 of sand from offshore to the beaches at a cost of $28.5 million, or $19.20/ yds^3, just over twice as costly per cubic yard as the earlier nourishment project. The substantial majority of that sand (approximately 1,070,000 yds^3) was added to the beaches of the Oceanside littoral cell at seven different sites. Averaging all the beach profiles surveyed a year later indicated a very slight or negligible advance of six feet in beach width (Griggs and Kinsman, 2016). Including the SANDAG projects of 2001 and 2011, a total of 10,034,000 cubic yards of sand has been placed on the beaches in the Oceanside littoral cell, averaging ~141,000 cubic yards per year (Table 4).

As of February 2023, SANDAG was in the preliminary planning stage for another regional beach sand project (RSBPIII) including a feasibility study and economic analysis.

Oceanside Beach Nourishment History

Year	Volume *cubic yards*	Source
1940	4,000,000	Dredging of Agua Hedionda Lagoon
1964-1985	1,100,000	Construction of San Onofre Nuclear Generating Station
1966	690,000	San Juan Creek and local marine terrace deposits
1964	94,000	San Juan Creek
1982	1,300,000	San Luis Rey riverbed
Total 1940-2000	**7,184,000**	**Average of ~138,000 cubic yards per year**
2001	1,780,000	SANDAG- Offshore sties
2011	1,070,000	SANDAG-Offshore sites
Total 1940-2011	**10,034,000**	**Average of ~141,000 cubic yards per year**

Table 4: Beach Nourishment History for the Oceanside Littoral Cell

Sand Sinks or Losses

Submarine Canyons: Sand entering the Oceanside Littoral Cell moves southward in the direction of the net alongshore transport and eventually leaves the shoreline and enters the heads of La Jolla and Scripps submarine canyons (Figure 6) which are within a few hundred yards of the shoreline, just offshore from Scripps Institution of Oceanography (Inman, 1976). These canyons extend offshore in a southwesterly direction for approximately thirty-three miles, eventually depositing sediment into San Diego Trough, although it is widely believed that La Jolla Submarine Canyon is not a functioning sink for beach sand at the present time (Runyan and Griggs, 2006b). Based on field studies made between 1984 and 1987 by Moffatt & Nichols Engineers, Inc. for the US Army Corps of Engineers (Wiegel, 1994), it was estimated that the sand capture rate for Scripps Submarine Canyon was between 18,000 and 40,000 yds^3/yr. Wiegel (1994) points out that this volume is considerably lower than estimates and calculations that have been made for the net littoral transport to the south (which will be discussed subsequently). It was also concluded in those earlier studies that Carlsbad Submarine Canyon, which lies nearly offshore of Agua Hedionda Lagoon, was not presently an active sink for littoral sand. However, a 2020 report by Poseidon Resources (Channelside) LP and Michael Baker, International on the dredging of Agua Hedionda includes a detailed bathymetric map of the northern Oceanside Cell including the head of Carlsbad Submarine Canyon (Figure 12). The bathymetry indicates that the canyon extends shoreward to a depth of at least 50 feet, which is within the depth range of offshore sand transport at the Oceanside Harbor breakwater. There is the potential, then, that the canyon head may be serving as a sink for sand moving downcoast near Agua Hedionda.

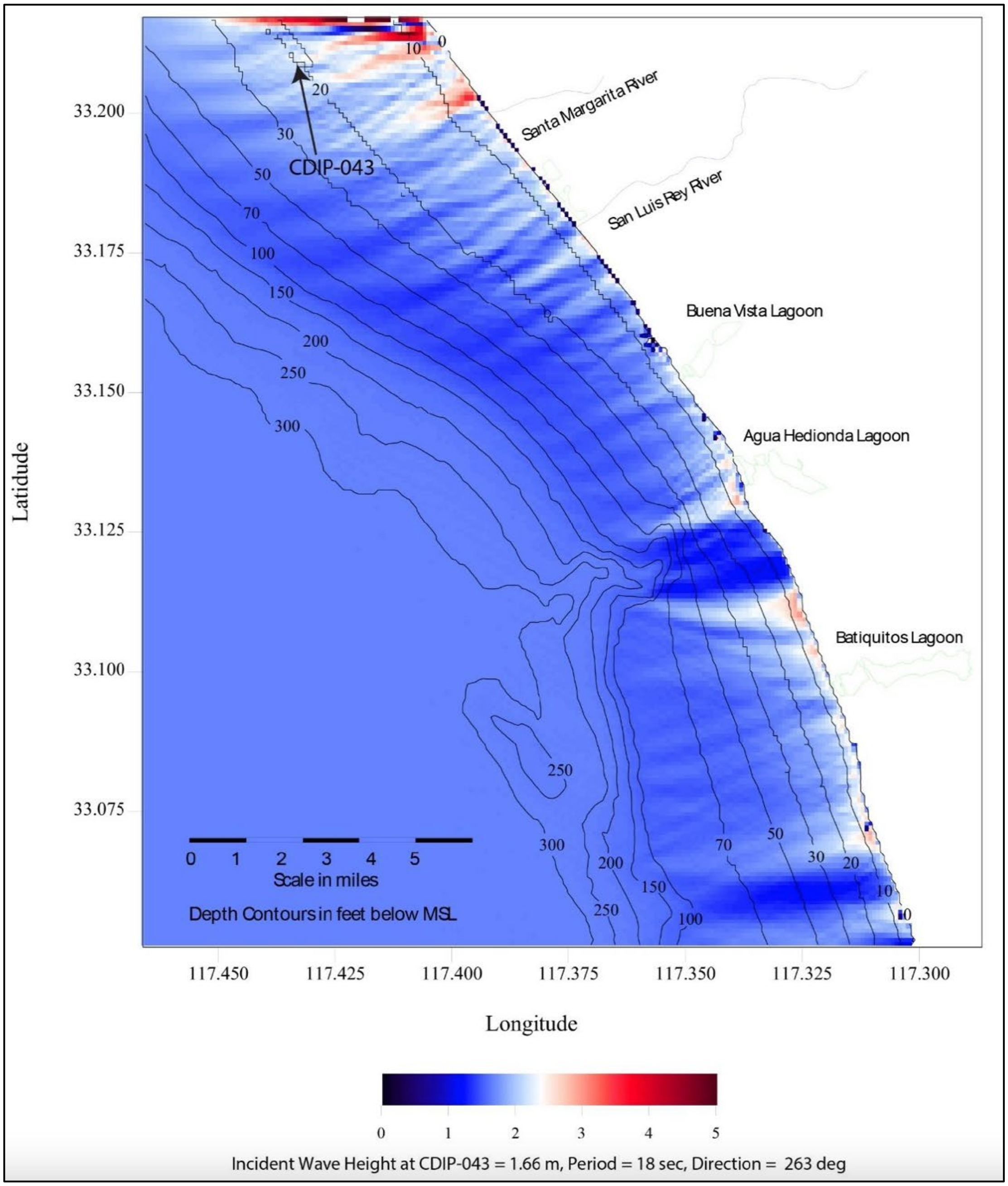

Figure 12: Detailed bathymetry of the northern Oceanside Littoral Cell showing the head of Carlsbad Submarine Canyon extending shoreward to a depth of at least 50 feet.

Offshore Bar at Oceanside Harbor: Dolan et al (1987), by comparing National Ocean Survey Sheets for 1934 and 1971-72, described an offshore bar near the entrance to Oceanside Harbor offshore of the breakwater: "The accretion band extends offshore for about 1.5 miles near Oceanside Harbor and then turns parallel to the existing bottom contours at depths between 40 and 60 ft." The accretion band elongates a considerable distance to the south, appearing to reach the 5-mile point where the analysis was terminated (Figure 13). This pattern of accretion indicates offshore deflection of littoral sand by the harbor's north breakwater, and subsequent southerly transport induced by a coast-parallel current outside the surf zone (Wiegel, 1994). According to Dolan et al. (1987), if the deposition dates to the initial construction of the Del Mar Boat Basin in 1942 (30 years of deflection and offshore transport of littoral drift), then the total offshore deposition translates into an average annual accretion rate of ~144,000 yds^3/yr. (or a total of 30 yrs. X 144,000 yds^3/yr. = 4,320,000 yds^3). If it is assumed that the formation of this offshore bar did not develop until after the expansion of the Oceanside Harbor complex in 1961, the average offshore sediment loss would be approximately 440,000 yds^3/yr. (Table 5). The third scenario is that the offshore deflection was initiated in 1958 when the northerly or upcoast jetty of the original Del Mar Boat Basin was extended to form a breakwater (Figure 14). Dolan et al. also believe that the gross drift arriving from the south may be partially deflected offshore as well.

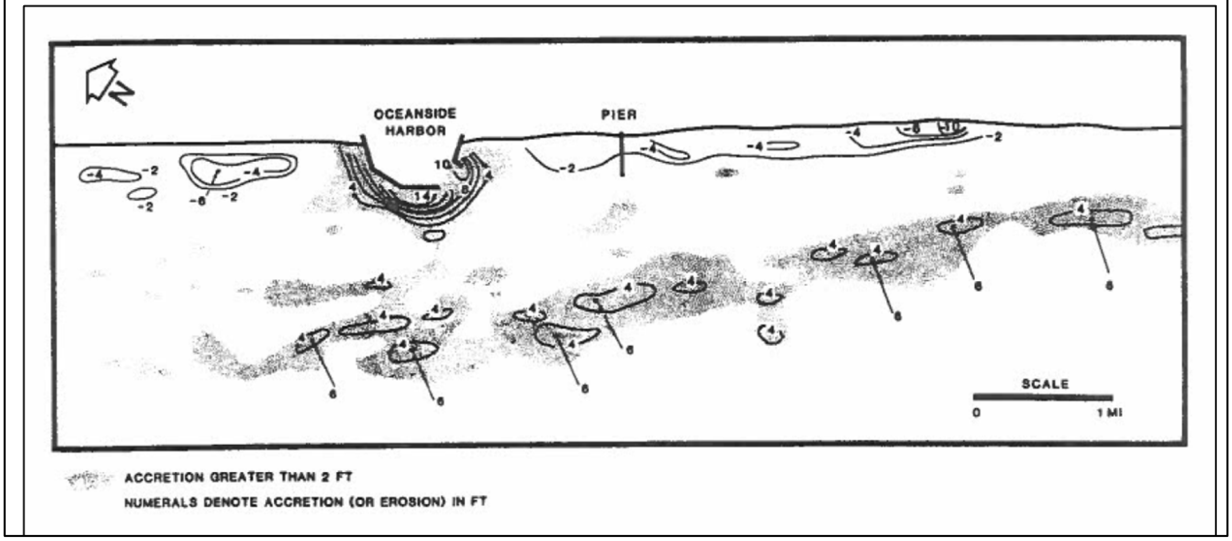

Figure 13: Historical changes in bathymetry off Oceanside Harbor between 1934 and 1972, showing shore-parallel sand bar that has accumulated extending offshore and downcoast from Oceanside Harbor breakwater, and erosion of nearshore areas.

Inman and Jenkins (1985) write that the extended breakwater created a rip current system that deflected the littoral sediment offshore (Figure 14). They calculated that the rip currents deflected and deposited 1,580,000 yds^3 of sediment between 1942 (when the Del Mar Boat Basin was constructed) and 1950, which amounts to an average rate of 197,500 yds^3/yr. An additional 1,065,000 yds^3 was deposited between 1950 and 1972. Combining these two volumes totals about 2,645,000 yds^3 carried offshore between 1942 and 1972 or an average of 88,170 yds^3/yr. (Table 5). This volume is significantly lower than the value calculated by Dolan et al. (1987), which speaks to the challenges and uncertainties involved in determining offshore volume changes.

The extent of offshore deflection of littoral drift at the breakwaters, reaching as far as 1.5 miles from the beach, extending downcoast of at least five miles and to water depths of sixty feet is striking (Wiegel, 1994), and is likely a major reason for the loss of Oceanside's beaches. What is known, from all the best available science (Dolan et al., 1987; Inman and Jenkins, 1985; Wiegel, 1994; Patsch and Griggs 2006a; Patsch and Griggs 2006b) is that this offshore bar is a major sink for sand in this cell due to large rip currents deflected offshore along the north jetty.

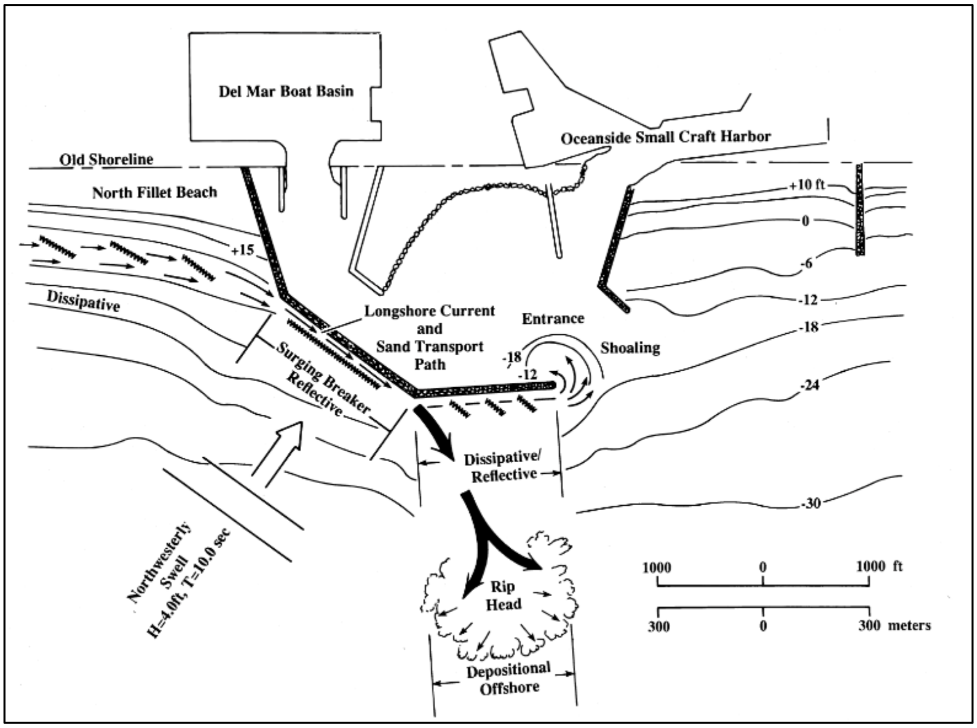

Figure 14: Del Mar Boat Basin with breakwater that has led to formation of rip current and offshore transport of littoral drift along breakwater extension (from Inman and Jenkins, 1983 & 1985).

Loss to the Offshore Bar

Average annual accretion rate *cubic yards per year*	**Source**	
144,000	Dolan et al (1987)	Scenario 1
440,000	Dolen et al (1987)	Scenario 2
197,500	Inman and Jenkins (1985)	Scenario 1
88,170	Inman and Jenkins (1985)	Scenario 2

Table 5: Loss of sediment to the offshore bar located seaward of Oceanside Harbor

Historic Changes in Beach Widths

The fundamental motivation behind the considerable number of studies of the Oceanside Littoral Cell has been the severe narrowing and ultimately loss of most of the beaches between the Oceanside Harbor and Carlsbad because of the impact of the breakwater on littoral sand transport. There have been literally dozens of studies, many by the Army Corps of Engineers, who planned and constructed the harbor and who accepted responsibility for the downcoast problems.

Documentation of historic beach widths is the most common approach to determining how beaches have changed over time and offers perspective on littoral drift direction(s) and rates. Vertical aerial photographs provide the best long-term evidence for beach width changes, although all aerial photographs vary somewhat in their resolution and scale, which can affect their usefulness.

The oldest available vertical aerial photographs of the Oceanside area were taken in 1932 and 1939 (UCSB Aerial Photo Library), a decade before the Del Mar Boat Basin was built. These, and many subsequent photographs, were analyzed to assess the natural condition of the shoreline and beach width prior to the development of the Del Mar Boat Basin and the Oceanside Harbor and also changes that took place following construction. Beach surveys on the ground have also been conducted throughout the Oceanside Littoral Cell. These capture shorter time periods, however, and are much more labor intensive to both collect and analyze.

Sixteen years ago, Chenault (2007) evaluated the changes in beach widths throughout the entire Oceanside Cell in order to assess the impacts of changes in sediment supply, wave conditions and human intervention. She restricted her analysis to the highest quality vertical aerial photographs, and used those from 1946, 1955, 1963, 1975, 1980, 1986, 1996, and 2001. Measurements were made using georeferenced photographs (corrected for any distortion) and the Digital Shoreline Analysis System (DSAS) extension in ESRI's ArcView software. Beach width was calculated as the distance between the wet/dry line and the back beach. Beach width was measured at ~160-foot intervals for 28 miles of coastline on these eight sets of photographs spanning the 55-year period from 1946-2001. The oldest photos analyzed were, however, taken four years after the completion of the Del Mar Boat Basin (in 1946), so likely did not reflect the natural or pre-harbor condition of the beaches.

Beach width in Chenault's North Oceanside segment (extending 1.8 miles south of the San Luis Rey River mouth to Oceanside Avenue; Figure 15) narrowed slightly from north to south with distance from the river mouth, from about 20 to 80 feet at the northern end to 0-100 feet to the south. During this 55-year time span, the beach widths fluctuated but with no clear trends. The 1963 and 1986 photos show significantly wider beaches. The increase in beach width in 1963 was due to placement of nearly 4.8 million yds^3 of material dredged during the construction of the Oceanside Harbor that was placed on the north Oceanside beach. The wider North Oceanside beaches in the 1986 photos may well be a residual effect of the major winters of 1981-82 and 1982-83 when rainfall and terrestrial and bluff erosion were high, and streams discharged large volumes of sediment to the coast. Mean beach widths in North Oceanside fluctuated between 50 and 270 feet during the 1946-2001 period with a long-term average of about 150 feet (Chenault, 2007).

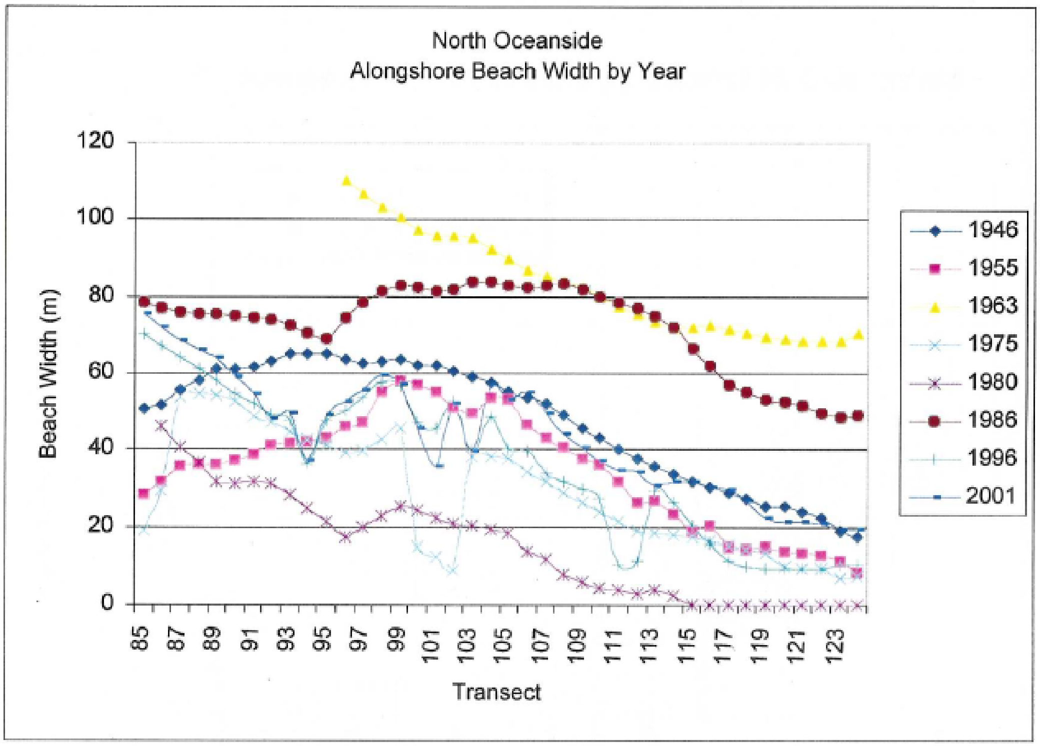

Figure 15: Historical beach widths in North Oceanside (in meters; Chenault, 2007)

Chenault's (2007) South Oceanside section of shoreline is about 1.2 miles long and extends from Oceanside Avenue to Buena Vista Lagoon. There were no houses on the ocean side of S. Pacific Street in the 1932 aerial, although there was a roadway (The Strand) out on the beach (Figure 16). There were just a few structures on the beach in the 1939 photo (Figure 17). By 1946, however, houses and multi-residential units had been built on most parcels on the ocean side of S. Pacific Street. These appear to have been at least partially constructed on the beach and partially on the outer edge of the low marine terrace for nearly the entire 2.2 miles of shoreline from just south of the Oceanside pier to Buena Vista Lagoon (Figure 18). The homes and other structures on what appear to be the back beach have potentially covered up to 100-125 feet of shoreline west of S. Pacific Street. This coverage totals approximately thirty-two acres of beach which has essentially been permanently lost. These homes and other structures are now almost all armored with rock revetments suggesting that they were built at beach level, which has no doubt contributed to significant loss of beach. This process is known as *passive erosion* (Griggs, 2005) or *coastal squeeze* and is the same process that occurs when the position of the back beach is fixed by a seawall or rock revetment; with a continuing rise in sea level, the beach will gradually be flooded and lost. This back beach development appears to be a significant – and apparently undescribed - reason for the decline in beach width along the Oceanside shoreline south of the pier.

Figure 16: February 1932 aerial photograph of the Oceanside shoreline showing wide beaches north and south of the pier which narrow to the south.

Figure 17: April 1939 aerial photograph of shoreline north and south of Oceanside pier, showing beach narrowing to the south to Carlsbad.

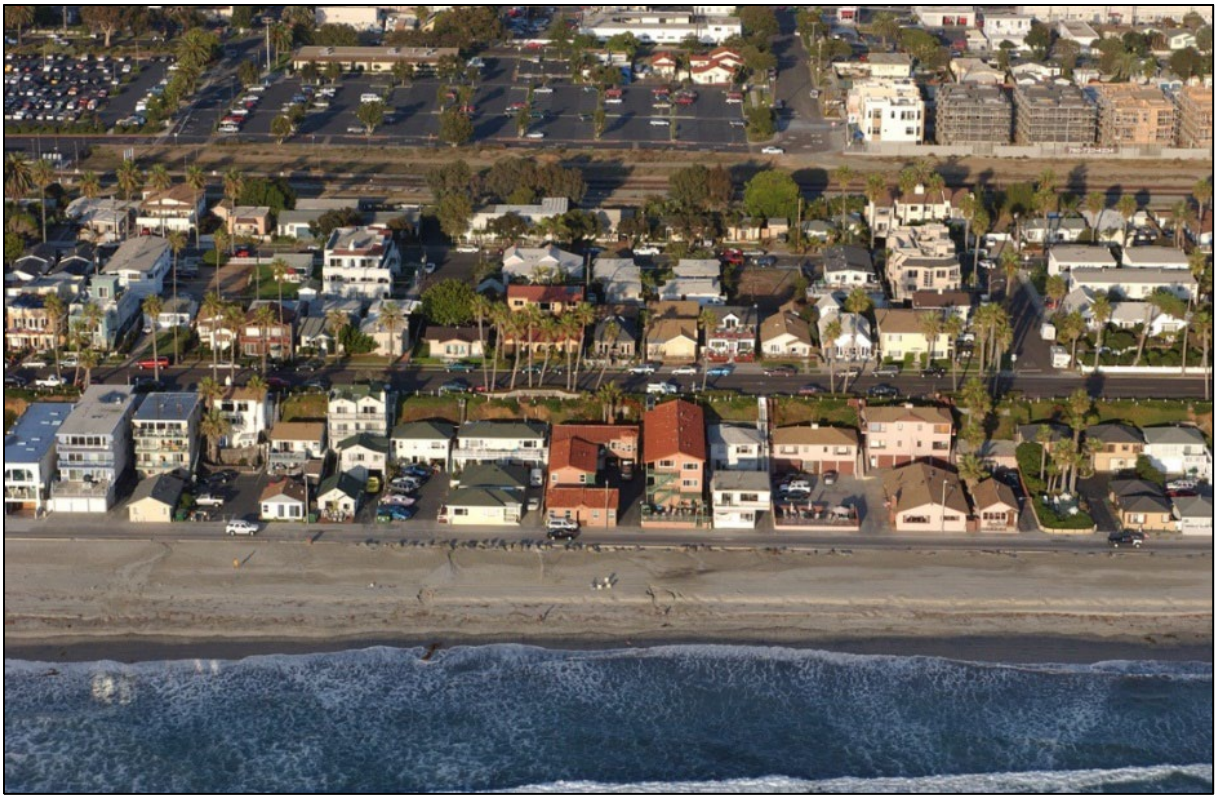

Figure 18: Homes built at least partially on the back beach shoreward of S. Pacific Street (2004- California Coastal Records Project – Kenneth and Gabrielle Adelman)

South Oceanside beach widths fluctuated between 1946 and 2001 but showed no net erosion or accretion trends. Long-term average beach width in this area was about 80 feet, but widths ranged from 0 to 160 feet (Figure 19), significantly narrower than the beaches of North Oceanside. Most of the significant changes in beach width resulted from direct human activity along the shoreline, such as beach nourishment (1963), harbor construction, or placement losses due to houses or other buildings built directly on the beach.

Chenault (2007) did not find any longer-term correlations with ENSO or PDO climate cycles, but beaches did respond to episodic storm events (Chenault, 2007; Orme, et al., 2011). Cyclonic winter storms during 1978-1979 and 1980-1981, and the powerful El Niño event of 1982-1983, generated large floods, powerful waves, and frequent cliff failures which all contributed abundant sediment to the littoral system. The 1978-1981 storms delivered more fluvial sediment to the Oceanside Littoral Cell than all other years of record combined (Grandy and Griggs, 2009). Large floods on the San Luis Rey River yielded more than 4.6 million yds^3 of sediment to the coast in 1979 and more than 1.3 million yds^3 in 1980 (Inman and Jenkins 1999). Despite this influx, beaches in the cell were much narrower in 1980 than earlier, essentially because southerly storm waves promoted strong scour from San Elijo northward to Oceanside (Kuhn and Shepard 1984). In contrast, by 1986, these beaches had not only recovered to pre-1980 widths, but on average were wider than for any other year studied. Most pronounced beach widening occurred near the San Luis Rey estuary and decreased away from there.

The earliest aerial photos used by Chenault (2007) were from 1946, four years after the construction of the Del Mar Boat Basin (initial harbor construction in 1942 with breakwater extension in 1958), which had a major impact on downcoast beaches. It is important, therefore, to evaluate typical beach widths prior to 1942. Additionally, one of the major sources of littoral sand, the San Luis Rey River, immediately upcoast from Oceanside, was dammed in 1922 with the formation of the Henshaw Reservoir, the only reservoir on the main stem of the river. The total watershed area of the San Luis Rey River is 565 mi^2, with the Henshaw Reservoir impounding 209 mi^2 or 39% of that drainage. This reduced the average annual sand and gravel contribution to the shoreline from ~130,000 yds^3 to ~40,000 yds^3, a decrease of approximately 90,000 yds^3 annually (Willis and Griggs, 2003).

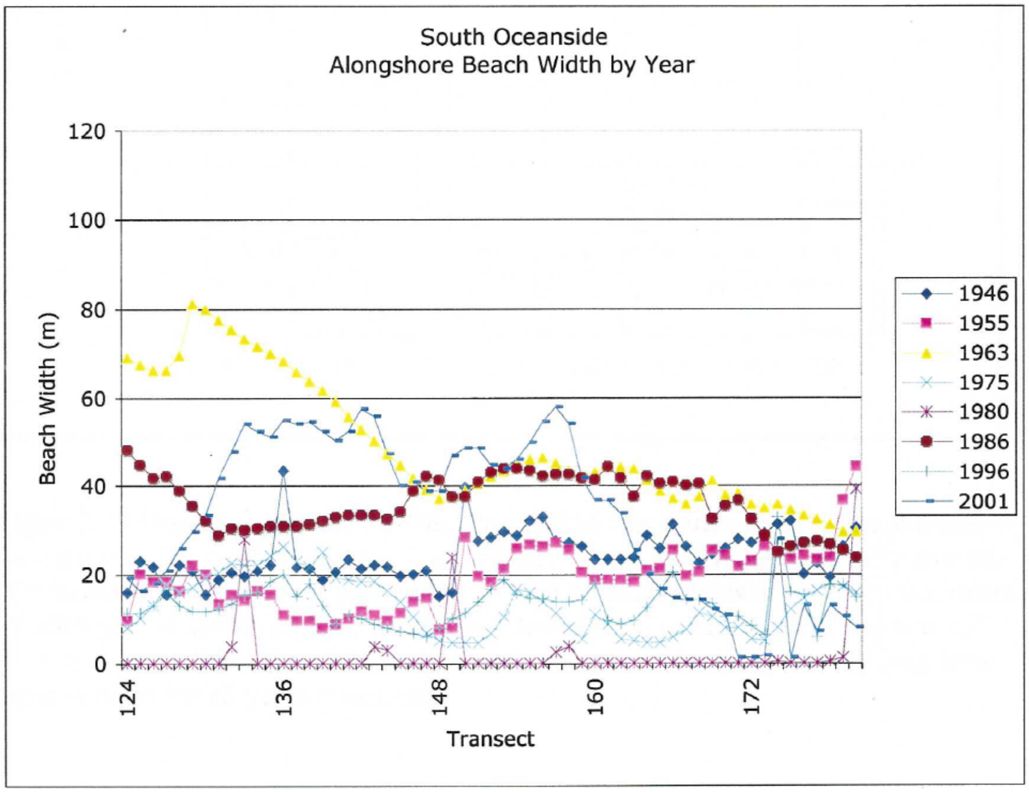

Figure 19: Historical beach widths in South Oceanside (in meters; Chenault, 2007)

While there is anecdotal information and older photographs of the wide Oceanside prior to any human alterations or impacts on sand supply and beaches, there does not appear to be any quantitative measurements. The pre-harbor construction vertical aerial photographs were analyzed to gain more insight. The oldest set of aerial images found were taken on February 28, 1932, so would be expected to show a narrower winter beach; however, the beach is quite wide. These photos preceded harbor construction but were taken ten years after the San Luis Rey River was dammed. Beach widths in these photos were greatest from the mouth of the San Luis Rey River to the Oceanside pier and averaged about 315 feet (Figure 16). The beach width gradually narrows to the south to about 100 feet and then widens again to roughly 150 feet at Alta Loma Creek. The beach to the south appears to be backed by low dunes with some vegetation. South of the creek mouth the shoreline morphology changes and the beach is now backed by a low bluff as the area of dry beach narrows to essentially non-existent along the

Carlsbad shoreline. The low bluffs continue to the entrance of Agua Hedionda Lagoon with virtually no dry beach there in the February 1932 photographs.

Observations of the relationship between beach width and cliff or bluff slope indicate that where a beach is narrow or non-existent, marine (wave) erosion dominates and the bluff or cliff is steep to near-vertical (Emery and Kuhn, 1982; Griggs and Kinsman, 2016). Conversely, where beaches are wide, waves rarely attack the cliffs or bluffs and terrestrial processes (slumping, sliding, rills and gullying, for example) dominant cliff erosion and produce more gentle slopes. The low steep bluffs along the Carlsbad shoreline are a good indicator that there were never wide permanent sandy beaches here and that marine erosion has dominated. The oldest aerial photographs (1932 and 1939; Figures 16 & 17) prior to harbor construction confirm this conclusion.

The 1939 aerial photos were taken on April 16 so should be more representative of summer conditions than the February 1932 photos. Again, these photos were taken prior to harbor construction, but after the Henshaw reservoir was created. A wide beach exists north of the pier, but like in the 1932 photo, it narrows gradually to the south or downcoast.

The next aerial photo analyzed was taken on December 30, 1946 (the earliest or oldest photo used by Chenault (2007)), after construction of the Del Mar Boat Basin but prior to the development of the public Oceanside Harbor (Figure 20). While the Santa Margarita River discharges over a mile upcoast from the northern jetty of the harbor, southerly littoral transport has built a wide sand spit that has forced the river mouth about 3/4ths of a mile south of the river mouth. Sand has also begun to build up against the northern jetty, although the beaches downcoast from the harbor (which is now four years old), do not yet appear to have been affected or narrowed by sand impoundment at the harbor.

Aerial photographs from April 1953, ten years following harbor construction, indicate additional sand accumulated against the north jetty and sediment filling the harbor entrance (Figure 21). Beach widths at the Oceanside pier have been reduced to about 225 feet, which continue to narrow to 60-75 feet proceeding to the south towards Carlsbad.

Figure 20: December 1946 aerial photo of Oceanside coast

The 1958 aerial photo taken in February reveals that the north jetty of the harbor has now been extended southward about 1400 feet (Figure 22). A large volume of sand has accumulated against the south jetty confirming that for at least a portion of the year that littoral drift moves north. The dry beach is very narrow or virtually non-existent south of the San Luis Rey River, although this is a spring photograph, so beach width would be expected to be narrower than summer conditions. Yet, comparing this photograph to the winter and spring photos from 1932, 1939 and 1946, the 1958 image shows a significant reduction in beach widths throughout Oceanside.

Figure 21: Oceanside shoreline in April 1953 showing decreased beach widths along the entire Oceanside shoreline compared to 1946 image.

Figure 22: Aerial photograph from February 27, 1958

Directions and Rates of Longshore Sediment Transport

Quantification of coarse sediment transport is challenging for a number of reasons, whether in a river or along the shoreline. Much of this transport in either location takes place under remarkably high flow or high wave conditions, which are extremely difficult, if not impossible to measure in place. The high energy events that transport much of the sediment are also typically episodic which also makes measurements particularly challenging to capture. Along the shoreline, littoral transport takes place over a wide zone of wave breaking and turbulence, perhaps several hundred feet or more, and because of all of these conditions, actual direct field measurements under large wave conditions are nearly non-existent.

Another factor that makes determination of a single value for longshore sediment transport direction and rate highly questionable are the temporal changes in the processes driving the transport. Longer-term trends in oceanic conditions have now been connected to the Pacific Decadal Oscillation or PDO. Between 1945 and 1977, the coast of California experienced a cooler or negative PDO period (Figure 23). This period was generally drier, with less rainfall, fewer large El Niño (or ENSO – El Niño-Southern Oscillation) storm events. Around 1978, however, the Pacific Decadal Oscillation shifted to a positive or warmer period with generally greater rainfall, more frequent and larger El Niños with larger waves arriving from the southwesterly direction, which transported littoral sand to the north and hit the California coast hard and produced major damage during the winters of 1978, 1982-83, and 1997-98. The PDO has shifted several times since 1999 (Figure 23).

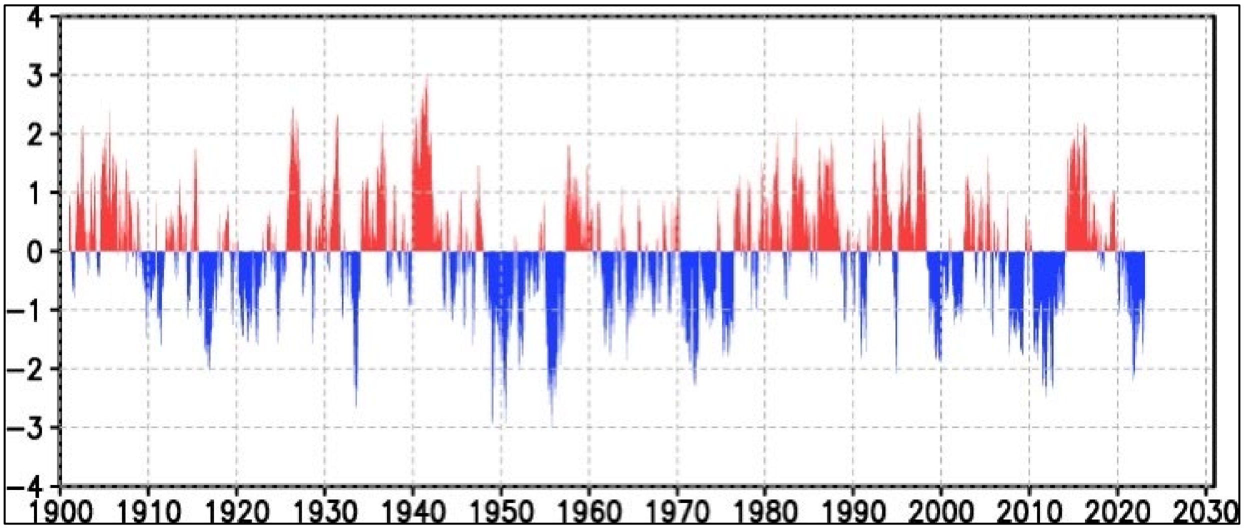

Figure 23: Pacific Decadal Oscillations from 1900-2022 with warmer stormier periods in red and cooler calmer cycles in blue.

Winter waves reaching the southern California coast typically arrive from the northwest and they are generated by North Pacific storms. These waves drive longshore sediment transport downcoast or to the south. Summer waves, on the other hand, typically arrive from the south or southwest, and drive longshore transport along the Oceanside coast to the north. Thus, the overall climatic trends in the Pacific basin determine which of these wave sources will dominate the wave climate along the southern California coastline over decadal time periods.

The shorter-term seasonal or annual difference in the direction of wave approach also leads to shifts in sand transport along this stretch of coast, as do the wave shadows created by the offshore Channel Islands (Figure 24). Many previous studies have recognized these seasonal reversals in both the direction and rate of longshore sand transport with these two dominant patterns (Marine Advisors, 1960; Inman, 1976; Hales,1978; Inman and Jenkins, 1983; Seymour and Castel, 1984; Moffatt and Nichol, 1990).

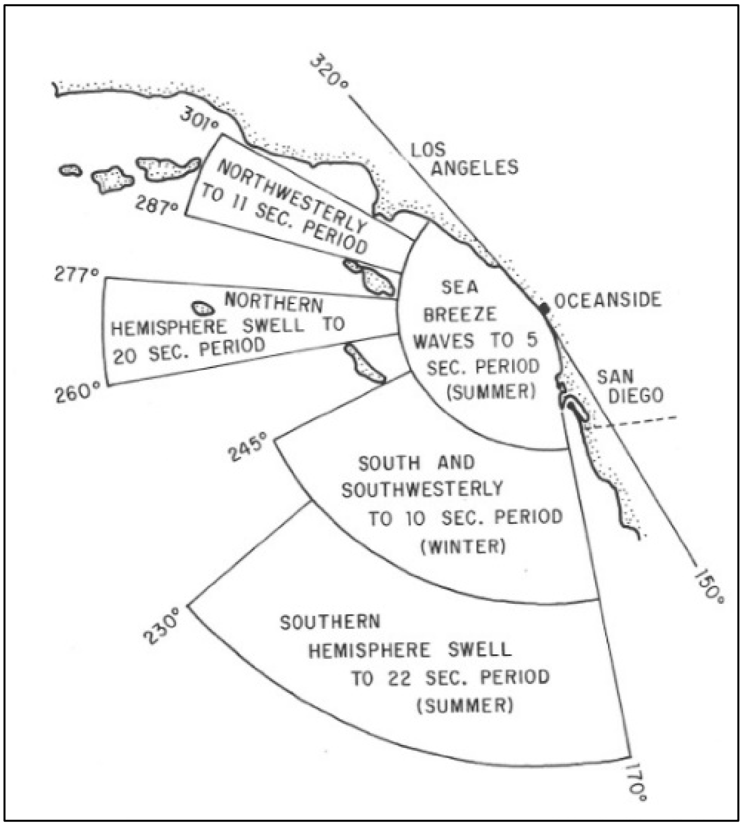

Figure 24: Wave exposure for Oceanside is affected by the wave shadows created by the offshore Channel Islands (from Marine Advisors, 1960)

There have been at least five previous studies that have estimated or attempted to quantify longshore sand transport, or the rate of littoral drift, in the Oceanside Littoral Cell (Table 6). Several of these have used available offshore wave data to calculate wave energy and then have converted these to values of potential littoral drift, which is the theoretical amount of sand that could be transported by the offshore wave energy were the sand available. With much of the Oceanside shoreline now covered with cobbles after having the original sand supply greatly reduced or removed, potential littoral drift calculations do not accurately reflect actual longshore transport on cobble beaches.

Longshore Sediment Transport Estimates

Location	Estimated Gross Northern Transport Rate cubic yards per year	Estimated Gross Southen Transport Rate cubic yards per year	Estimated Net Longshore Transport Rate cubic yards per year	Direction	Source
Oceanside Littoral Cell	545,000	760,000	215,000	South	Marine Advisors (1961)
	N/A	N/A	250,000	South	Inman (1976)
	N/A	N/A	260,000	South	Inman & Jenkins (1985)
	550,000	740,000	194,000	South	Hales (1979)
	934,000	N/A	106,000	South	USACE, (1991); Tekmarine, Inc., (1978)
Oceanside Harbor Southside	N/A	N/A	146,000	South	Patsch & Griggs, 2006
	N/A	N/A	240,000	South	Patsch & Griggs, 2021
Oceanside	553,000	807,000	254,000	South	Inman & Jenkins (1983)
Oceanside	541,000	643,000	102,000	South	Hales (1978)

Table 6: Longshore sediment transport estimates for Oceanside, CA.

Marine Advisors (1960 & 1961) was the first effort to quantify longshore sand transport. They used the best available wave data at that time (now 60 years ago) and calculated a net southerly longshore transport rate of 215,000 yds^3/yr. (Table 6). A few years later, Inman (1976) carried out a very comprehensive study of the Oceanside Littoral Cell following harbor construction and used several different approaches to evaluate the rate of longshore sediment transport. Also using available offshore wave data, and potential littoral drift theory, Inman calculated a net longshore potential sand transport to the south of 215,000 yds^3/yr. Inman also measured the rate of sand accretion in the harbor entrance along with the associated loss of sand from Oceanside beaches downcoast of the harbor. Based on entrance channel dredging and downcoast beach erosion, Inman concluded that the net longshore transport of sand along the shoreline of the Oceanside littoral cell was about 250,000 yds^3/yr. to the south. He also averaged the annual dredging volumes from the harbor at that time (1942-1969) which was ~250,000 yds^3/yr. He also looked at the rate at which sand was trapped by the short jetty at Agua Hedionda Lagoon, about five miles downcoast from the harbor (160,000 yds^3/yr.). In addition to the net potential drift, Inman and Jenkins (1985) used wave statistics and calculated gross potential littoral drift, determining that an average of ~740,000 yds^3/yr. of sand is carried to the south, while ~550,000 yds^3/yr. is transported north. This gives an average gross or total transport rate of 1,290,000 yds^3/yr. and an average net southerly transport rate of ~194,000 yds^3/yr., a somewhat lower rate than was determined by other methods (Table 6).

Because of the shoreline problems that were created by the construction of the Oceanside Harbor complex and the range of directions and values determined for longshore sediment transport by the above studies and several others carried out by the Corps of Engineers, Lyndell Hales (1978) from the U.S. Army Engineers Waterways Experiment Station in Vicksburg, Mississippi, was tasked with a conducting a comprehensive evaluation t of the coastal and oceanographic conditions (Coastal Processes Study of the Oceanside, California, Littoral Cell). This report is an exhaustive assessment of the physical and oceanographic setting as well as longshore sediment transport (as of 1978). The section in Hales' report dealing specifically with wave conditions and exposure, and the determination of longshore sediment transport and the uncertainties and variables involved in the calculations, extends for twenty pages including graphics. Hales' report points out that available wave data have increased over time; that there are both offshore and nearshore data, and that slight differences in the angle at which the waves approach and break along the shoreline dependent on nearshore bathymetry can produce significant differences in the direction and rates of potential littoral drift calculated. Additionally, as discussed earlier, there are extended periods during the year when the dominant waves arrive from the northwest, the southwest, and from directly offshore as local wind swells. These findings have been confirmed by the most recent assessment (GHD, 2021) which included a table of the longshore transport values determined in many of the previous studies.

What became evident many years ago in previous studies is that littoral drift in the Oceanside Littoral Cell shifts or changes direction during the year. Southern swells during the spring and summer drive longshore transport of sand to the north and larger north Pacific swells from the northwest and west during fall and winter move sand to the south. The durations of these periods can change from year to year and over decadal time scales as well. Thus, there are multiple factors that affect the many calculations of potential littoral drift that help to explain the differences that have been determined.

As discussed earlier, Patsch and Griggs (2006b and 2021) used long-term average annual harbor dredging rates as reasonable proxies or checkpoints for littoral drift rates for California's major littoral cells. Using this proxy, the best available estimate of littoral drift around Oceanside Harbor (using the entire 57 years of dredging records from 1965-2022) is ~240,000 cubic yards per year (Figure 25). It is important to understand, however, that in this area, the direction of littoral drift changes seasonally and the configuration of the entrance jetties/breakwaters traps sand moving both up and down coast (Inman, 1976; Tekmarine, 1978; Hales, 1979; Inman & Jenkins, 1985; and GHD, 2021). The north jetty configuration (and possibly the south jetty as well) has also led to large volumes of littoral sand being directed offshore, which has formed the large offshore bar oriented parallel to the coast (Dolan et al., 1987) discussed in the previous section.

Seasonal changes in the direction of wave approach along the northern portion of the Oceanside Littoral Cell generate longshore sediment transport both to the north and the south. Southerly transport dominates, however, with average rates of ~240,000 cubic yards per year based on long-term dredging volumes (Figure 25).

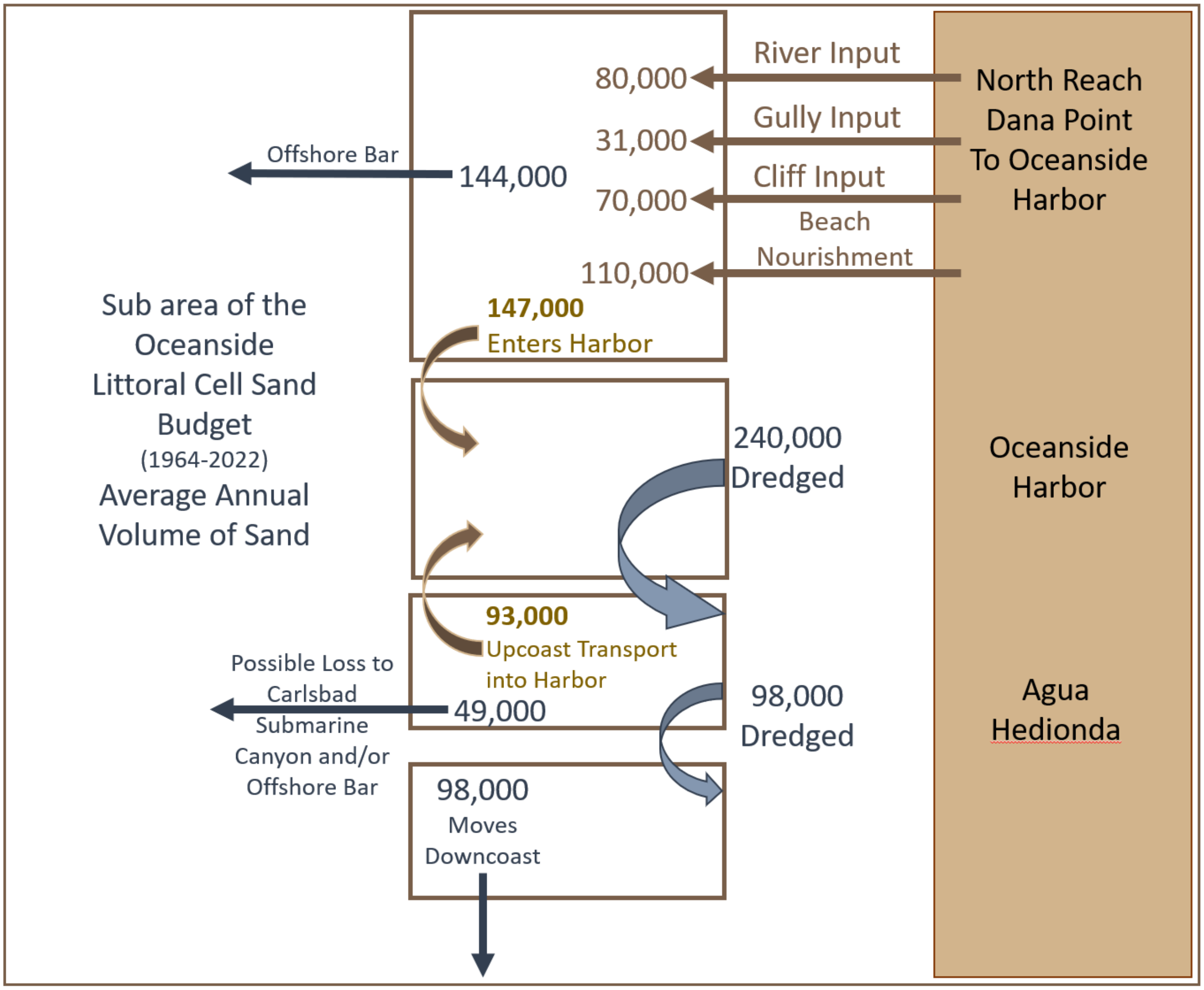

Figure 25: Sand Budget for a portion of the Oceanside Littoral Cell (1964-2022).

Recommendations for Future Work

There are recommendations that we strongly suggest being implemented as part of any additional future study of the northern Oceanside Littoral Cell to help answer some unresolved questions regarding the littoral sand transport rate and direction along this reach of coast:

1. ***Timing of dredging of Oceanside Harbor***. Because the direction of littoral sand transport varies seasonally in response to different directions of wave approach, it makes sense to perform annual Oceanside Harbor dredging in those months roughly between October and March (or those months when wave approach is normally from the northwest) to ensure that dredged material is transported southward and doesn't re-enter the harbor.
2. ***Surveying shoreline where dredge spoils are deposited***. As part of the process of downcoast disposal of dredged material, a beach and nearshore survey program should be planned and initiated at the disposal site and immediately downcoast on a repeated basis so the transport pathway of the sand can be documented.
3. ***Investigation of sand bar/band offshore of Oceanside Harbor:*** Dolan et al. (1965), delineated an offshore sand bar or accretion band that extended offshore for about 1.5 miles at the Oceanside Harbor and then turned parallel to the existing bottom contours at a depth of 40 to 60 feet and extended downcoast for about five miles where their investigation terminated. This 1965 discovery may provide an explanation for the significant loss of littoral sediment from the shoreline at the Oceanside Harbor breakwater that moves downcoast. The detailed COE bathymetry from 2015 and any sediment data from the vibracores collected offshore of the harbor and downcoast should be evaluated to determine if the sediments are indicative of active sediment transport. If active transport is indicated, it is recommended that the 2015 bathymetric survey and coring be continued downcoast to determine the total extent of this feature. This would not only allow for the determination of how much total littoral sediment has been and continues to be lost offshore but will also provide useful information for a potential source of sand for future nourishment.
4. ***Potential role of Carlsbad Submarine Canyon***. A 1988 study by Moffatt and Nichol for the COE on submarine canyons offshore San Diego County concluded that Carlsbad Submarine Canyon (which lies offshore of Agua Hedionda) *"extends shoreward across the continental shelf to a water depth of about 100 ft. Littoral sand is not carried to the canyon head at that depth".* This conclusion was based on earlier work by Fischer et al. (1983) that reported results of their study of the canyon:

   > *"Carlsbad Submarine Canyon was reported inactive but not completely filled at the present time by Fischer et al. (1983). Their interpretation of seismic records obtained shoreward of the canyon head (0 to 100 foot depths) indicated the shoreface and continental shelf bottom was bare rock or covered with a very thin layer of sediment. North of the canyon Fischer et al. (1983) reported the sediment volume above bedrock and out to a depth of 100 feet to be about 4 x 10^3 yds^3/lineal alongshore foot. South of the canyon they found it to be only one-*

> *fifth that value, or 0.8 x 10^3 yds^3/ft. They attributed this large north-to-south decrease in shelf sediment volume to entrapment in estuaries south of Oceanside. However, it could also be the result of canyon infilling at a previous time or at the present time. Emery (1960) and Inman and Frautschy (1966), identified Carlsbad Canyon as a current inactive feature that they considered to have been the downcoast end of a littoral cell when sea level was lower.*
>
> *Shepard and Emery (1941) found active canyons that extend near the present coast have hard-packed channels in deep water composed of sand, gravel, or rock. They found inactive canyons were partially filled with mud. The axis of Carlsbad Submarine Canyon contains relatively soft mud and Shepard and Emery (1941) assumed it was presently inactive based on that sedimentologic evidence."*

A more recent bathymetric map included in a 2020 report by Poseidon Resources (Channelside) LP and Michael Baker, International however, indicates that the head of Carlsbad Submarine Canyon extends into depths as least as shallow as 50 feet, and is therefore within the dept range (40-60 feet) that littoral transport has been directed offshore to form a major sand bar at the Oceanside Harbor. If an investigation of the offshore sand bar extending downcoast from Oceanside Harbor is undertaken, it is recommended that the most shoreward extent of Carlsbad Submarine Canyon and bottom sediments between the canyon head and the shoreline be investigated to determine whether or not littoral sand moves offshore at this point.

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