Title
Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions

Permalink
https://escholarship.org/uc/item/9rg8617t

Journal
Journal of Coastal Research, 22(2)

ISSN
0749- 0208

Authors
Young, A P
Ashford, S A

Publication Date
2006-03-01

DOI
10.2112/05–0548

Journal of Coastal Research	22	2	307–318	West Palm Beach, Florida	March 2006

Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions

Adam P. Young and Scott A. Ashford

Department of Structural Engineering
Jacobs School of Engineering
University of California, San Diego
9500 Gilman Dr.
La Jolla, CA 92093-0085, U.S.A.
adyoung@ucsd.edu

ABSTRACT

YOUNG, A.P. and ASHFORD, S.A. 2006. Application of airborne LIDAR for seacliff volumetric change and beach-sediment budget contributions. *Journal of Coastal Research,* 22(2), 307–318. West Palm Beach (Florida), ISSN 0749-0208.

Coastal seacliff erosion in California threatens property and public safety, whereas coastal beach erosion threatens the coastal tourism economy. While coastal rivers, seacliffs, and gullies supply the majority of littoral material to California beaches, the relative contributions of these sources are coming into question. These beach-sediment sources must be accurately quantified to formulate proper solutions for coastal zone management.

This study evaluated the seacliff and coastal gully beach-sediment contributions to the Oceanside Littoral Cell using airborne LIght Detection And Ranging (LIDAR). Seacliff and gully beach-sediment contributions were compared with coastal river beach-sediment contributions estimated in previous studies. This study took place over a relatively dry period from April 1998 to April 2004.

The results indicate that seacliffs provided an estimated 67% of the beach-size sediment to the littoral cell, followed by gullies and rivers at 17% and 16%, respectively, over the period of the study. The total volumetric seacliff erosion rates were used to back-calculate average annual seacliff face retreat rates for the study period. These rates ranged from 3.1 to 13.2 cm/yr and averaged 8.0 cm/yr for the Oceanside Littoral Cell.

Comparison of these results to previous studies suggests that the relative seacliff sediment contributions may be higher than previously thought. Conversely, beach-sediment contributions from gullies were significantly lower compared with previous studies. This is likely because of the episodic nature of gullying and the relatively dry study period. Nevertheless, the results of this study indicate that seacliff sediment contributions are a significant sediment source of beach sand in the Oceanside Littoral Cell, and the relative annual seacliff beach-sand contribution is likely higher than previous studies indicate.

ADDITIONAL INDEX WORDS: *Littoral cells, shoreline changes, erosion rates, coastal erosion, coastal mapping, San Diego County.*

INTRODUCTION

Coastal cliff erosion is a serious problem, affecting 86% of the California coast (GRIGGS and SAVOY, 1985). Erosion of seacliffs, often manifested in the form of episodic slope failures, threatens public safety as well as public and private property. Seacliff erosion, however, is also a source of sediment to the beach, the erosion of which is a threat to the coastal tourism economy. In San Diego County alone, coastal tourism contributes in excess of $200 million a year to the local economy. The problems associated with seacliff and beach erosion will only increase if projections of sea level rise, ranging from 9 to 88 cm by 2100 (IPCC, 2001), become a reality.

The majority of littoral material supplied to California beaches comes from coastal rivers, seacliffs, and gullies. In Southern California, all of these sediment sources are episodic in nature, as demonstrated by the seacliff failure illustrated in Figure 1, which delivered 890 m^3 of coarse sediment to the littoral system almost instantaneously. In order to formulate proper solutions to the problems associated with coastal beach erosion, the relative sediment source contributions to the beach-sand budget must be accurately quantified. Past efforts to evaluate volumetric change of seacliffs and seacliff sediment yields have been accomplished using a variety of techniques, including aerial photographs and topographic maps (BEST and GRIGGS, 1991; BOWEN and INMAN, 1966; DIENER, 2000; ROBINSON, 1988), empirical methods (EVERTS, 1990), long-term cliff top erosion rates (RUNYAN and GRIGGS, 2003), and softcopy photogrammetry (HAPKE, 2005).

The objective of this paper is to evaluate the seacliff and gully littoral contributions using airborne LIght Detection And Ranging (LIDAR) for the Oceanside Littoral Cell during a relatively dry period between April 1998 and April 2004. LIDAR is a type of remote sensing used to collect topographic data. LIDAR sensors pulse a narrow, high frequency laser beam at the Earth's surface and record the reflection time and angle of each pulse. Advances in airborne LIDAR sur-

---

DOI:10.2112/05–0548.1 received 30 June 2005; accepted in revision 18 October 2005.

Figure 1. Seacliff failure in Solana Beach, September 28, 2004.

veying allow accurate data to be collected over large areas. Successive surveys can be used to quantify volumetric change over time. Even though the available LIDAR data covers a much shorter time scale than other traditional methods (only a few years versus decades), its high resolution data yields quantitative estimates of the volume of total sediment liberated by the erosion process.

STUDY AREA

The Oceanside Littoral Cell, located in the San Diego County region (Figure 2), spans a 77-km stretch of coastline from Dana Point to La Jolla (Inman and Frautschy, 1966). The cell is categorized by narrow sand and cobble beaches backed by steep seacliffs cut into uplifted marine terraces. The majority of the Oceanside Littoral Cell contains both residential and commercial development on the cliff top, with the exceptions of the Camp Pendleton Military Reservation and San Onofre State Park. Steep cliffs characterize 70% of the study area, with occasional alternating lowlands at coastal river mouths and lagoons. A majority of the seacliffs are approximately 25 m in height (height range: 2–110 m), and are generally composed of two primary geologic units. The lower unit consists of lithified Eocene and Miocene mudstone, shale, sandstone, and siltstone sedimentary rocks (Kennedy, 1975). The upper unit is composed of unlithified Pleistocene terrace deposits. The lower unit is stronger and more resistant to erosion; however, both units are highly erodible, with long-term erosion rates of 8 to 43 cm/y (Benumof and Griggs, 1999).

The study area was divided into 10 sections based on general stratigraphy and major river incisions. The sections are shown in Figure 2 and described in Table 1 by the section boundary, cliff length within the section, average cliff height, percentage of beach-size sand in the cliffs, and the dominating erosional processes based on Emery and Kuhn's (1982) seacliff classification (Figure 3) and section designation.

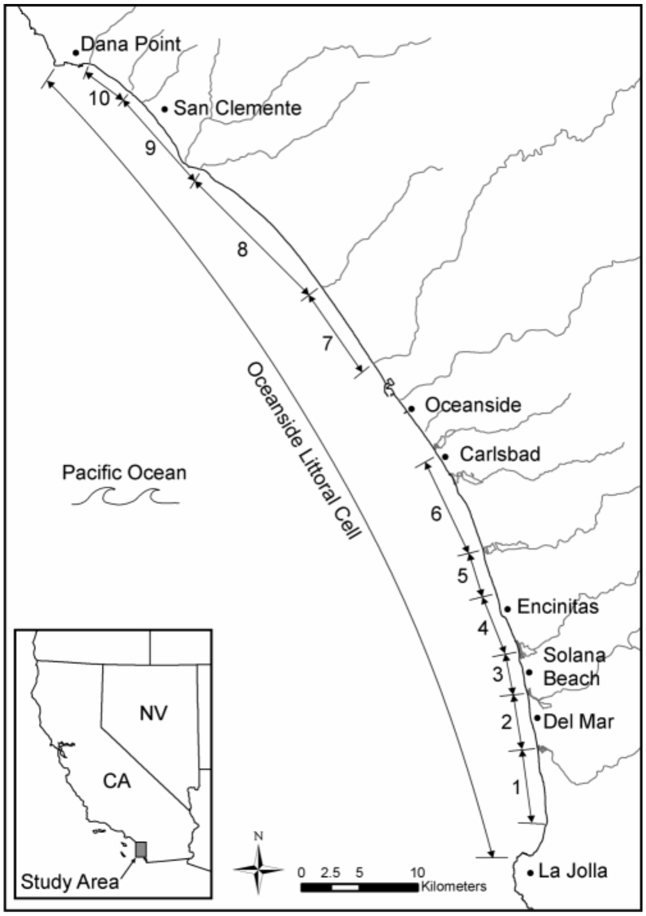

Figure 2. Study location map and section boundaries.

In addition to quantifying the total volume of material eroded from the seacliffs during the study period, it is also of interest to estimate that portion of the volume that may remain on the beach. Very fine-grained sediments typically are not retained on the beach because of the high energy wave environment in this area. Therefore, it was necessary to determine the percentage of seacliff sediments that are large enough to remain in the littoral system. Hicks (1985) determined that there is a sediment size diameter boundary or "littoral cutoff diameter" that describes whether a sediment grain is of sufficient size to be retained on the beach. Sediments with a diameter larger that the littoral cutoff diameter are retained on the beach, whereas sediments with a diameter smaller than the littoral cutoff diameter are not. The littoral cutoff diameter for the Oceanside Littoral Cell has been evaluated at 0.06 mm (Everts, 1990) and 0.0875 mm (Runyan and Griggs, 2003). The percentage of seacliff sediments larger than the littoral cutoff diameter (%LCD) has been previously estimated for sections of the Oceanside Littoral Cell by Robinson (1988), USACE-LAD (1984), Everts (1990), and Runyan and Griggs (2003). Values from these previous studies were selected that best correlate with the section boundaries used in this study.

The section between Carlsbad and Camp Pendleton (cov-

Table 1. *Section descriptions for the Oceanside Littoral Cell.*

Section No.	Section Name	Southern End	Northern End	Length of Cliffs (m)	Average Cliff Height (m)	% of Beach-Size Sand in Seacliffs (%LCD[1])	Dominating Erosional Process
1	Torrey Pines	SIO Campus	Penaquitos Lagoon	6,550	88.0	42[2]	Marine[3]
2	Del Mar	Penaquitos Lagoon	Power House Park	2,550	17.9	75[4]	Equal[3]
3	Solana Beach	San Dieguito River	San Elijo Lagoon	2,800	23.5	75[4]	Equal[3]
4	Cardiff	San Elijo Lagoon	Moonlight Beach	3,740	25.1	80[4]	Equal[3]
5	Leucadia	Moonlight Beach	Bataquitos Lagoon	3,980	26.0	80[4]	Equal[3]
6	Carlsbad	Bataquitos Lagoon	Oak Avenue	6,910	16.5	80[4]	Marine[3]
7	Camp Pendleton	Santa Margarita River	Las Flores Creek	4,970	17.4	54[2]	Subaerial[3]
8	San Onofre	Las Flores Creek	San Onofre Creek	11,230	38.6	71[2]	Subaerial[3]
9	San Clemente	San Onofre Creek	Secunda Deshecha	7,130	28.6	80[5]	Subaerial
10	Dana Point	Secunda Deshecha	San Juan Creek	3,830	37.2	80[5]	Subaerial

[1] %LCD = percentage of sediments in the seacliffs larger than the littoral cutoff diameter.
[2] Robinson (1988).
[3] Emery and Kuhn (1982).
[4] USACE-LAD (1984).
[5] Everts (1990).

ering the City of Oceanside) was not included in this study. This section consists of heavily urbanized low-relief seacliffs, beaches, river mouths, and lagoons. In this section the bluff face has been either heavily armored or built upon with residential development. Therefore, the seacliffs in this section were assumed to not contribute significant amounts of beach sand to the littoral cell. The San Clemente and Data Point sections were analyzed, but were not included in any cell-wide calculations. These sections are removed from wave action by the coastal railway and beach development, and therefore it is currently unclear whether sediment from these sections actually enters the littoral system.

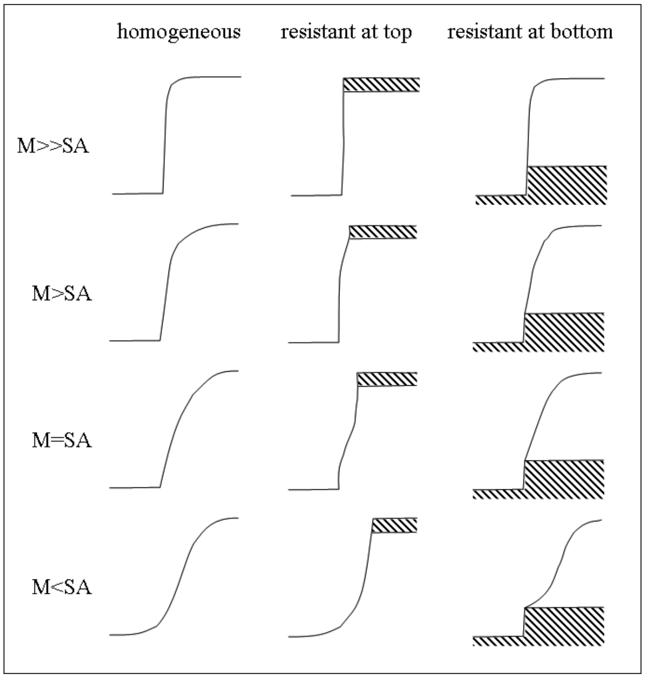

Figure 3. Matrix of seacliff profiles with respect to relative erodibility of the cliff top and cliff base, and the relative effectiveness of marine (M) versus subaerial (SA) erosion. Figure modified from Emery and Kuhn (1982).

The Oceanside Littoral Cell receives waves from three primary sources: northern hemisphere swell, southern hemisphere swell, and local seas. Deep-water waves undergo a complex transformation because of island shadowing, refraction, diffraction, and shoaling before reaching the coastline. Waves that arrive at the coast provide energy, removing seacliff failure deposits and eroding exposed seacliffs at the base.

San Diego has a semiarid, Mediterranean climate characterized by mild, sometimes wet winters and warm, very dry summers (MILLER, 2005). San Diego is also influenced by the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Strong El Niño events are associated with anomalously high precipitation during the winter rainy season. The rainy season of San Diego begins in the fall and ends in the spring. For the purposes of this paper, we assume that the study period (April 1998 through April 2004) covers water years 1999–2004 (*i.e.,* October 1, 1998, through September 30, 2004). This is a reasonable assumption because negligible precipitation occurred between April and October 1998 and between April and September 2004.

BACKGROUND

Previous studies of the Oceanside Littoral Cell evaluated seacliff and gully sediment contributions to the littoral cell using topographic maps (ROBINSON, 1988), empirical methods (EVERTS, 1990), and long-term erosion rates (USACE-LAD, 2003; RUNYAN and GRIGGS, 2003). A summary of results from these studies and others is shown in Table 2.

ROBINSON (1988) evaluated three sections using topographic maps from 1889 (scale 1:10,000) and 1968 (scale 1:24,000): San Onofre, Camp Pendleton, and Torrey Pines. These sections covered approximately between 450 and 900 m from the coast inland. Elevation contours were digitized from the maps into X, Y, Z data and gridded into 8-m cells. ROBINSON (1988) then evaluated the volumetric change and

Table 2. *Summary of annual beach-sediment contributions to the Oceanside Littoral Cell from previous studies.*

			Annual Beach-Sediment Volumes (m³/yr)						
Section	Sediment Source	Actual or Natural	Robinson (1988)	Everts (1990)	USACE-LAD (2003)	Runyan and Griggs (2003)	Willis *et al.* (2002)	Flick (1993)	Inman and Masters (2005)
Torrey Pines	Seacliffs, gullies, terraces	Natural	42,300	—	—	—	—	—	—
Camp Pendleton	Seacliffs, gullies, terraces	Natural	90,300	—	—	—	—	—	—
San Onofre	Seacliffs, gullies, terraces	Natural	138,200	—	—	—	—	—	—
Solana Beach	Seacliffs	Actual	—	—	3184	—	—	—	—
Cardiff	Seacliffs	Actual	—	—	2397	—	—	—	—
Leucadia	Seacliffs	Actual	—	—	4168	—	—	—	—
Oceanside Littoral Cell	Seacliffs	Natural	—	32,900	—	51,400	—	—	—
Oceanside Littoral Cell	Seacliffs	Actual	—	—	—	42,000	—	—	—
Oceanside Littoral Cell	Gullies, terraces	Both	—	—	—	219,400	—	—	—
Oceanside Littoral Cell	Gullies	Natural	—	296,700	—	—	—	—	—
Oceanside Littoral Cell	Terraces	Natural	—	4000	—	—	—	—	—
Oceanside Littoral Cell	Coastal rivers	Actual	—	—	—	—	101,000	—	—
Oceanside Littoral Cell	Coastal rivers	Actual	—	—	—	—	—	112,000–203,000	—
Oceanside Littoral Cell	Coastal rivers	Natural	—	—	—	—	—	170,000–346,000	—
Oceanside Littoral Cell	Coastal rivers	Actual (dry)	—	—	—	—	—	—	19,100
Oceanside Littoral Cell	Coastal rivers	Actual (wet)	—	—	—	—	—	—	293,000
Oceanside Littoral Cell	Coastal rivers	Actual (average)	—	—	—	—	—	—	122,000

calculated the beach-sediment yield based on the %LCD in each section.

Everts (1990) developed an empirical method to hindcast and forecast linear seacliff toe retreat rates for the Oceanside Littoral Cell. The average annual seacliff toe retreat rates were calculated based on the frequency probability of storm events and associated seacliff toe retreat. The linear toe retreat rates ranged from 1.5 to 9 cm/yr. The annual seacliff toe retreat rates were then used to calculate the natural annual seacliff beach-sediment contribution (*i.e.,* excluding the effect of seacliff stabilization) to the littoral cell by using the following general equation:

$$Q_s = L_c \times R_l \times H_c \times \%\mathrm{LCD} \qquad (1)$$

where:
Q_s = natural annual seacliff sediment yield
L_c = length of seacliffs
R_l = linear rate of seacliff retreat
H_c = average height of seacliffs

USACE-LAD (2003) also used the general form of Equation (1) to calculate the annual sediment yields for Solana Beach and Encinitas. The average seacliff top retreat rates estimated by USACE-LAD (2003) ranged from 7.6 to 37.0 cm/yr. This study assumed that the cliff top would retreat to create a more stable slope, and therefore the annual beach-sediment volumes were reduced by one-half to account for this equilibrium. Because shoreline protection reduces the amount of littoral material supplied to the beaches, the natural annual beach-sediment contributions were adjusted downward to account for the percentage of protective devices, thus resulting in the actual contribution.

Runyan and Griggs (2003) calculated natural seacliff contributions to the Oceanside Littoral Cell using long-term (40–60 years) seacliff top retreat rates from both Benumof and Griggs (1999) and Moore, Benumof, and Griggs (1998). These linear seacliff top retreat rates ranged from 10 to 20 cm/yr. Seacliff beach-sediment yields were then calculated using the general form of Equation (1). Runyan and Griggs (2003) calculated the annual gully volume by subtracting their natural annual seacliff beach-sand volume from Robinson's combined seacliff and gully annual beach-sand volume. Runyan and Griggs (2003) also calculated the actual annual seacliff volume by reducing their natural annual beach-sand volume based on the percentage of shoreline armoring in each section.

The surfaces of coastal terraces can provide beach-sand to littoral system by means of subaerial erosion and small stream transportation. The terrace degradation sediment yield was estimated by Everts (1990) at 4000 m³/yr for the Oceanside Littoral Cell. For the purposes of this study, terrace surface yields were assumed to be negligible in the overall sediment budget because of the dry study period and relatively low volume reported by Everts (1990).

Rivers can provide a significant amount of beach-sand to the littoral cell. However, the natural average annual sediment load of California coastal rivers has been significantly reduced by the development of the coastal watershed through flood control and water storage dams (Brownlie and Tay-

LOR, 1981; FLICK, 1993; GRIGGS, 1987; INMAN and BRUSH, 1973; INMAN and JENKINS, 1999; WILLIS, SHERMAN, and LOCKWOOD, 2002). These studies indicate that the natural beach-sediment load of coastal rivers in the Oceanside Littoral Cell has been reduced by approximately one half. FLICK (1993) summarized several studies that estimate the actual long-term average annual coastal river beach-sediment flux to the Oceanside Littoral Cell at 112,000–203,000 m^3/yr. A more recent study by WILLIS, SHERMAN, and LOCKWOOD (2002) estimates the actual beach-sediment flux at 101,000 m^3/yr. It should be noted that the fluvial beach-sediment delivery to the littoral system is highly episodic in California. INMAN and JENKINS (1999) found that the average annual sediment flux during wet periods is five times higher compared to dry periods for California rivers, and that this episodicity is even more pronounced in Southern California. In fact, INMAN and MASTERS (2005) estimate the fluvial beach-sand flux in the Oceanside Littoral Cell for dry and wet periods at 19,100 m^3/yr and 293,000 m^3/yr respectively, which is approximately a 15 times difference for wet and dry periods.

Based on the studies presented above, the total annual amount of beach-sediment contribution from all natural sources combined (rivers, seacliffs, gullies, and terraces) would appear to range from just over 350,000 m^3/yr to nearly 550,000 m^3/yr. Of this total, the contribution of seacliff erosion is on the order of 10 to 15 percent, which is in agreement with conventional wisdom, whereas gully erosion appears to be the most significant source of beach sediment. It should be noted, however, that the contributions of gullies noted in EVERTS (1990) and RUNYAN and GRIGGS (2003) are directly related to the initial estimates of ROBINSON (1988). The data presented by ROBINSON (1988) is based on interpretation of old topographic maps and dominated by a limited number of extreme gully erosion events caused by altered drainage patterns associated with the construction of coastal highways in the Camp Pendleton and San Onofre sections. KUHN and SHEPARD (1984) documented several of these events, including the formation of a new canyon in the San Onofre section, which eroded landward 140 meters between 1968 and 1980, and Dead Dog Canyon in the Camp Pendleton section, which eroded landward 230 meters between 1932 and 1980. Below, we use airborne LIDAR data to quantify the combined contributions of seacliffs and gullies over the 6-year study period as an independent benchmark of the conventional wisdom, and then compare the LIDAR-developed contributions to estimates of river beach-sediment contributions for the study period.

METHODS

Topographic Change

In order to evaluate the topographic change of the seacliffs, two airborne LIDAR data sets were used that span a 6-year time period. The older data set was collected in April 1998 using NASA's Airborne Topographic Mapper (ATM, 1998). This survey was obtained from NOAA (2004). The second data set was collected in April 2004. This data set was provided by the Southern California Beach Processes Study, operated by the Scripps Institution of Oceanography. Both data sets were obtained in X, Y, Z format. The original point densities of the 1998 and 2004 data were 0.9 and 3.3 points per m^2, respectively. The X, Y, Z point data were interpolated into 0.5-m resolution grids using the ArcINFO 3-D Analyst (Version 9.0, 2004, Environmental Earth Science Research Institute, Redlands, CA). Grid interpolation was completed using inverse distance weighting.

After grid interpolation, the Oceanside Littoral Cell was divided into 10 sections for analysis. The change in elevation was evaluated for each section by subtracting the 2004 grid from the 1998 grid (Equation [2]). This procedure results in a grid showing the change in elevation over time. Negative cells indicate erosion and positive cells indicate accretion.

$$Z_{Change} = Z_{1998} - Z_{2004} \tag{2}$$

where:
Z_{Change} = cell change in elevation
Z_{2004} = cell elevation in 2004
Z_{1998} = cell elevation in 1998

Figure 4 shows the central portion of the Solana Beach grid displayed under a transparent shaded relief. The red areas in this figure indicate areas where significant erosion occurred during the study period. This figure shows numerous distinct upper seacliff failures as well as several sections of lower seacliff retreat. These calculations were performed using data from the base of the 1998 seacliff landward. No changes in beach volumes are included.

The potential error in the change grid can be primarily attributed to LIDAR measurement error, interpolation error, and vegetation. Error evaluation was done by computing the root mean square (RMS), which describes the average magnitude of change between the two data sets. Typical vertical RMS error for quantifying beach changes using airborne topographic LIDAR is 15 cm (SALLENGER *et al.,* 2003). This RMS value was not deemed to accurately quantify the error in this study, because it focused on high relief cliffs with partial vegetation in some areas. Therefore the RMS error was evaluated using a 400-m representative control section in Encinitas between Swami's and San Elijo State Beach. The control section consists of a partially vegetated slope and was assumed to have no significant change over the time period, because it was stabilized in 1960 using a rock revetment at the base, slope grading, and surface drainage control (KUHN and SHEPARD, 1984). The vertical RMS for this section was calculated using Equation (3) (FEDERAL GEOGRAPHIC DATA COMMITTEE, 1998).

$$RMS_Z = \sqrt{\frac{\sum_{i=1}^{n} (za_i - zb_i)^2}{n}} \tag{3}$$

where:
za_i = cell elevation in 2004
zb_i = cell elevation in 1998
n = number of cells

The RMS_Z of the control section was calculated at 21 cm. This value was then used as a threshold of acceptable error

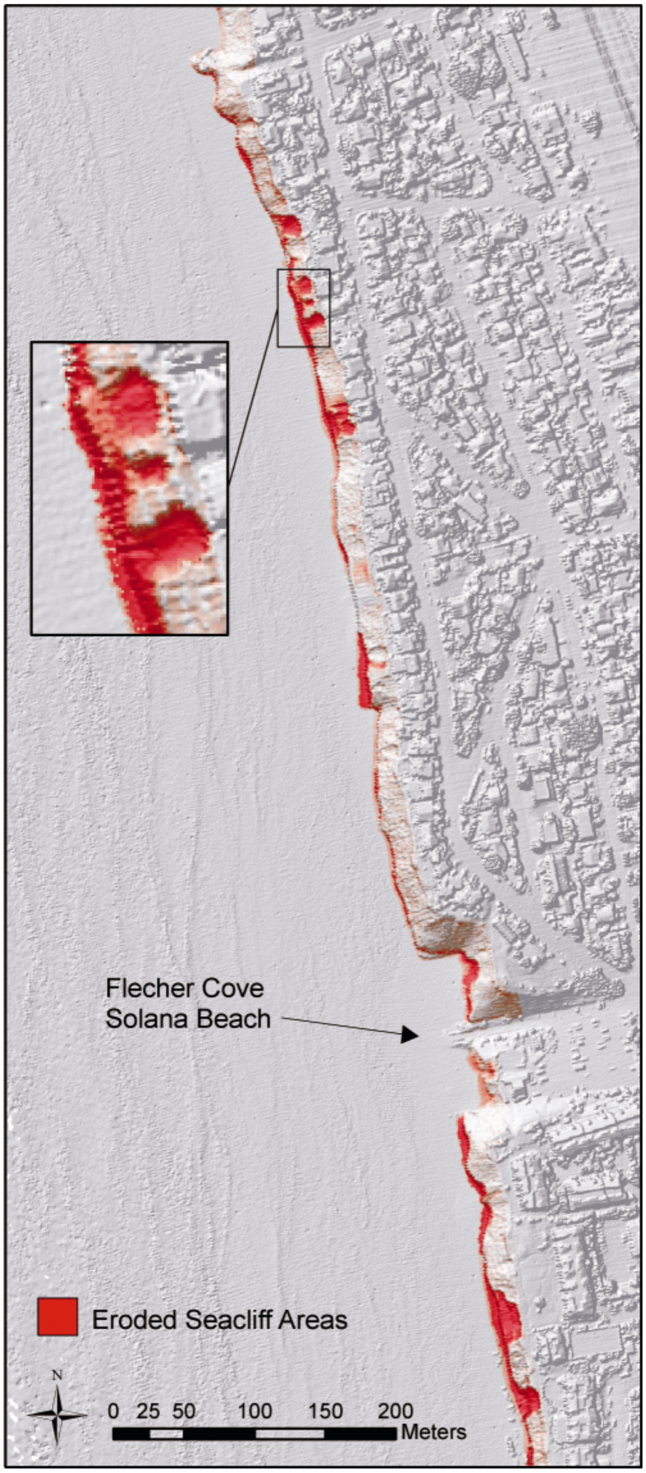

Figure 4. Erosion grid of central Solana Beach where red cells represent seacliff erosion that occurred between April 1998 and April 2004. Several upper cliff failures and sections of lower cliff retreat are shown in this figure.

Table 3. *Section error.*

Section Name	RMS (m)	Error (%)
Test section	0.21	—
Torrey Pines	1.28	16.4 (± 8.2)
Del Mar	1.07	19.7 (± 9.9)
Solana Beach	2.12	9.9 (± 5.0)
Cardiff	1.20	17.5 (± 8.8)
Leucadia	1.32	15.9 (± 8.0)
Carlsbad	0.81	25.9 (± 13.0)
Camp Pendleton	0.75	28.1 (± 4.1)
San Onofre	1.43	14.6 (± 7.3)
San Clemente	1.42	14.7 (± 7.4)
Dana Point	1.31	16.0 (± 8.0)
Oceanside Littoral Cell	1.32	16.0 (± 8.0)

for each cell. Each cliff section was isolated from the beach and cliff top development by clipping the change grids along the seacliff base and cliff top. Next, cells that showed erosion of 21 cm or more ($-\infty <$ cells < -21 cm from Equation [2]) were extracted from each section to produce a new erosion-only grid.

RMS_Z values were then calculated for each erosion grid. Statistical error for each section was calculated as a ratio based on the RMS_Z of the control section, using Equation (4) (ZHANG *et al.,* 2005). Table 3 summarizes the RMS_Z and percentage error for each section and weighted cell average.

$$Percentage\ Error = RMS_{Z(Control\ Section)}/RMS_{Z(Seacliff\ Section)} \qquad (4)$$

Other error in the grids may have come from interpolating over sharp edges or vegetation. Aerial LIDAR typically does not capture over vertical surfaces such as seacaves or notches. Therefore, changes that occurred in these areas were not evaluated. Complete LIDAR coverage was not available for Las Pulgas Canyon and a small portion of the Torrey Pines section, and these areas were also not evaluated.

The total eroded volumes were calculated for each section by summing the volumes of negative cells less than the threshold value of −21 cm. Cells that showed erosion values between 0 and −21 cm were removed to compensate for possible grid interpolation error.

Gullies were clipped out of the erosion grids to quantify the eroded gully volume. Gullies were removed from the total seacliff eroded volume because, although they did contribute beach sediment to the littoral cell, they did not contribute to the eroded volume of the seacliff face. Gullies in each section were identified using the generated digital elevation models and aerial photographs. For this project, gullies were defined as areas where significant subaerial erosion occurred because of concentrated terrace runoff and piping. These included extensive gully networks, coastal ravines, and canyons. An example of a well-developed gully network is shown in Figure 5. Subtracting the gully volumes from the total eroded volume in each section produced a seacliff erosion volume.

Areas that showed significant accretion and were determined to be landslide talus deposits were added to the eroded volume for correction. These volumes were added back in to the corresponding seacliff or gully section because they had not yet entered the littoral system. Talus deposits were identified as accretion areas found below significantly eroded ar-

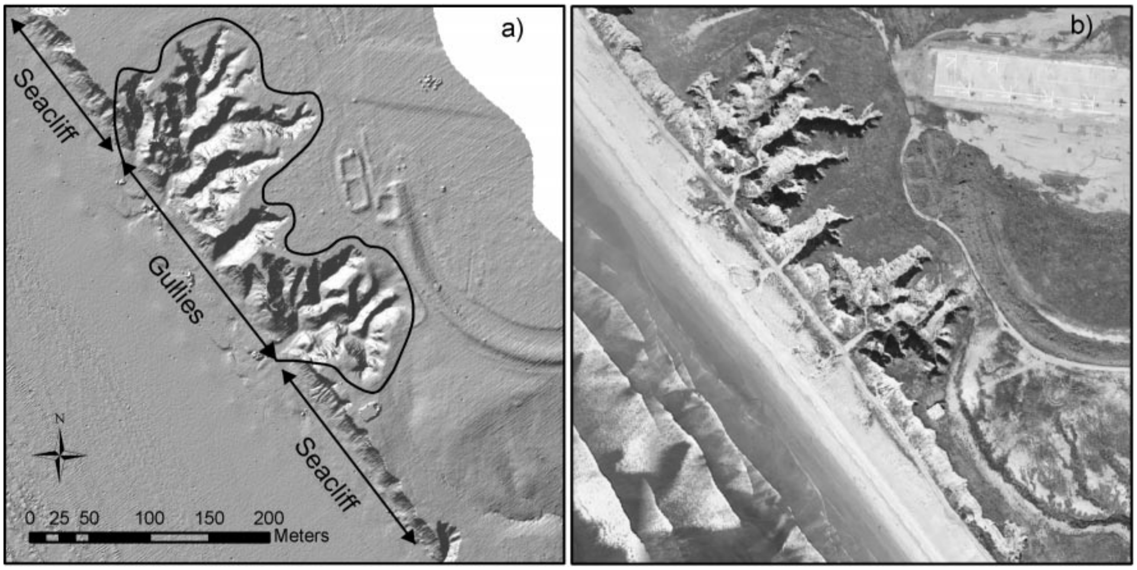

Figure 5. Example of the identification and boundary of an extensive gully network in the Camp Pendleton section. (a) Shaded relief map. (b) Aerial photograph.

eas. These deposits typically conformed to the shape of alluvial fan deposits, and were found at the base of the seacliff or in the bottom of the gullies. Coastal construction that occurred during the study period also resulted in some accretion areas. These areas were separated from the talus deposits and were not added to the eroded volume. Corrections were also made in heavily vegetated areas by removing the cells.

The total eroded volumes of seacliffs and gullies were then reduced to quantify the contribution of beach-sand-sized material, based on the %LCD values from Table 1. These volumes were then divided by the 6-year time span to produce average annual sediment volumes of beach-sand-sized material. Table 4 shows a section summary of total annual volumes and annual volumes reduced for %LCD. Section volumes were summed to quantify the average annual seacliff and gully beach-sediment contributions to the entire littoral cell. Note that the San Clemente and Dana Point sections were excluded from this calculation for reasons previously discussed.

Table 4. *Average annual eroded section volumes (m³/yr) from April 1998 to April 2004.*

	Total Eroded Sediment		Beach-Sand Content (total reduced for %LCD[1])	
Section Name	Gully	Seacliff	Gully	Seacliff
Torrey Pines	8300	26,400	3500	11,100
Del Mar	600	4900	500	3700
Solana Beach	0	8300	0	6200
Cardiff	0	5800	0	4600
Leucadia	0	5900	0	4700
Carlsbad	0	4000	0	3200
Camp Pendleton	7600	5500	4100	2900
San Onofre	16,700	57,100	11,900	40,500
Oceanside Littoral Cell[2]	33,200	117,900	20,000	76,900
San Clemente[2]	4700	7600	3800	6100
Dana Point[2]	0	4500	0	3600

[1] %LCD = percentage of sediments in the seacliffs larger than the littoral cutoff diameter.
[2] The total for the Oceanside Littoral Cells excludes the San Clemente and Dana Point sections.

Seacliff Beach-Sediment Contribution and Retreat Rate

Figure 6 shows the actual average annual beach-sediment contributions from the seacliffs per meter of cliff length for each section, as well as for the entire littoral cell. These val-

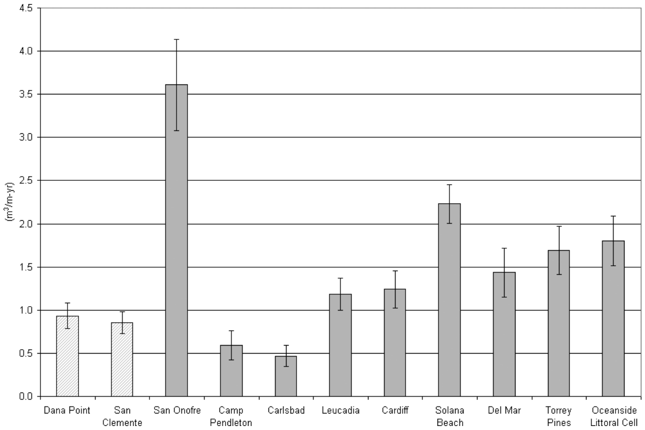

Figure 6. Actual average annual seacliff beach-sediment contributions per cliff length for the study area between April 1998 and April 2004.

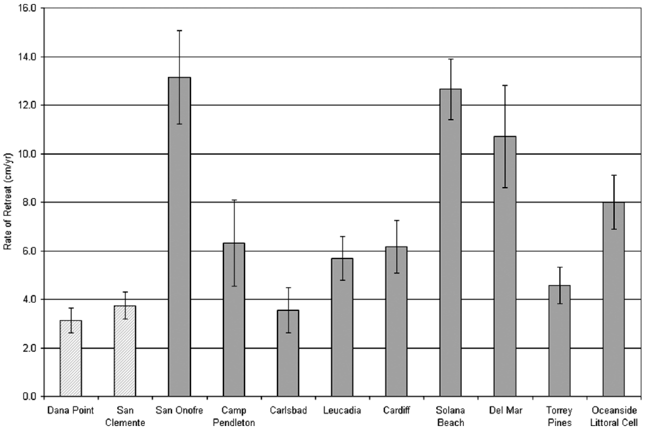

Figure 7. Actual average annual rate of seacliff face retreat for the study area between April 1998 and April 2004.

ues were calculated based on Equation (5). Error bars in Figure 6 were calculated based on the percentage error values from Table 3. The weighted average of seacliff beach-sediment volume per length of cliff for the entire Oceanside cell was calculated based on the section seacliff length.

$$R_{vs} = (V_{st} \times \%\mathrm{LCD})/(L_c \times T) \tag{5}$$

where:
R_{vs} = volumetric rate of sand contribution per length of seacliffs
V_{st} = total eroded volume from seacliffs
L_c = length of seacliffs (including armored sections)
T = time span

Figure 7 shows the actual average annual rate of seacliff face retreat for each section. The linear rate of cliff face retreat was calculated for each section based on Equation (1). This equation was rearranged to back-calculate the actual average annual rate of seacliff face retreat and is shown as Equation (6). A weighted average of seacliff face retreat for the entire Oceanside cell was calculated based on the section seacliff length. Error bars in Figure 7 were calculated based on the percent error values from Table 3.

$$R_l = V_{st}/(H_c \times L_c \times T) \tag{6}$$

where:
R_l = linear rate of cliff face retreat
V_{st} = total eroded volume from seacliffs
H_c = average seacliff height

The average section seacliff heights used in Equation (6) were evaluated by taking a profile parallel to the shoreline along the cliff using the ESRI ArcINFO (2004) profiler. The profiles were then averaged over the seacliff length to produce an average cliff height. These values are shown in Table 1.

The graphical representation of Equation (6) is shown in Figure 8. The geometry of this figure shows that Equation (6) is independent of the slope angle. Note that Equation (6) describes the average rate of retreat over the entire cliff face. This does not represent the actual seacliff top or seacliff base rate of retreat.

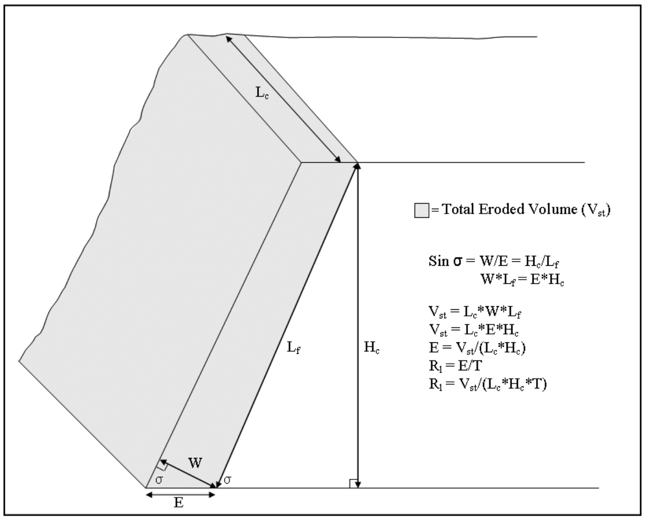

Figure 8. Typical seacliff geometry and the geometric relationship between seacliff retreat and the total eroded seacliff volume.

Precipitation and Coastal River Beach-Sediment Contributions

The Oceanside Marina rain gauge (#046377) was chosen as a representative rainfall indicator for the cell. This gauge was selected because it is centrally located and has a 60-year record to compare past precipitation with that of the study period. Monthly rainfall amounts were obtained from the WESTERN REGIONAL CLIMATE CENTER (2005). Monthly precipitation values were added to obtain annual values for each water year, extending from October 1 to September 30 of the later year. The average annual rainfall at the Oceanside Marina is 25.7 cm based on water years 1954 to 2004. The annual precipitation during the study period is shown in Figure 9. This figure shows that the study occurred during a relatively dry time period. Statistically, rainfall during the study time frame was 27% below average. The study period occurred between two heavy rain years, after the El Niño 1997–1998 event (46 cm) and before the 2004–2005 wet season (50 cm as of June 1, 2005, third wettest year in San Diego's recorded history).

Because this study spanned a relatively dry period, and given the episodic nature of California river sediment flux (INMAN and JENKINS, 1999), the average annual fluvial beach-sediment contributions reported in the background section would be overestimates of the beach-sediment flux for the study time period. Therefore, it was required to estimate the beach-sediment flux for the dry study period so a proper comparison could be made to the seacliff and gully beach-sediment contributions

Initially, an attempt was made to calculate the sediment flux using annual river flows and sediment rating curves. Unfortunately, many of the flow data were not available during

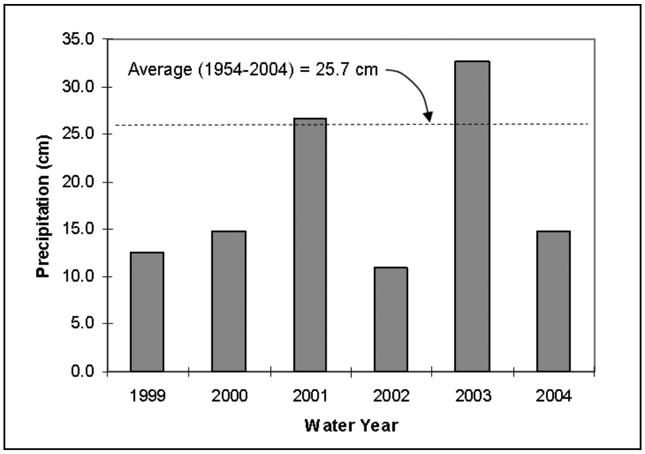

Figure 9. Precipitation at Oceanside marina for water years 1999–2004 (monthly values obtained from the Western Regional Climate Center [2005]).

the study time period. Therefore, the annual beach sediment for the study period was assumed to correlate with the dry average annual beach-sand flux reported by INMAN and MASTERS (2005) of 19,100 m³/yr (average of dry years from 1943 to 1977).

RESULTS

Based on the airborne LIDAR data, seacliffs and gullies yielded 76,900 m³/yr and 20,000 m³/yr of beach-sediment, respectively, during the study period (Table 4). The majority of the beach sediment from both the seacliffs and gullies originated from the San Onofre section. The volumetric rate of beach-sediment yield per length of shoreline ranged from 0.47 (Carlsbad) to 3.61 (San Onofre) m³/m-yr with a weighted average of 1.80 m³/m-yr for the entire Oceanside Littoral Cell (Figure 6). Figure 7 shows that the linear rate of seacliff face retreat ranged from 3.1 to 13.2 cm/yr with a weighted average for the littoral cell of 8.0 cm/yr. The highest seacliff face retreat rates were found in the Del Mar, Solana Beach, and San Onofre sections, where rates were all greater than 10 cm/yr. Statistical error for each section ranged from 9.9% to 25.9%, with an overall weighted cell average of 16.0% (Table 3).

DISCUSSION AND CONCLUSIONS

Figure 10 shows the estimated percentage of beach-sediment contributions from seacliffs, gullies, and rivers during the study period (excluding artificial nourishment). Seacliffs produced the majority of beach sediment at 67%, followed by gullies and rivers at 17% and 16% respectively. These percentages would likely change significantly during wet periods when all beach-sediment source volumes would increase appreciably, though how the relative volumes would change is not well understood. The average annual rate of river beach-sediment volumes has been estimated at 101,000 to 203,000 m³/yr (FLICK, 1993; WILLIS, SHERMAN, and LOCKWOOD, 2002). Even using the upper bound of these annual rates, the percentage of seacliff contributions is still significant. Increasing the seacliff yield marginally for more average climatic conditions and using recently evaluated average annual river beach-sediment yields of 101,000 m³/yr (WILLIS, SHERMAN, and LOCKWOOD, 2002) would put the seacliff beach-sediment contributions upwards of 50% of the beach-sediment budget. This level of contribution from the seacliffs is supported by recent research by HAAS (2005) based on sediment provenance analysis of beach sand in the study area.

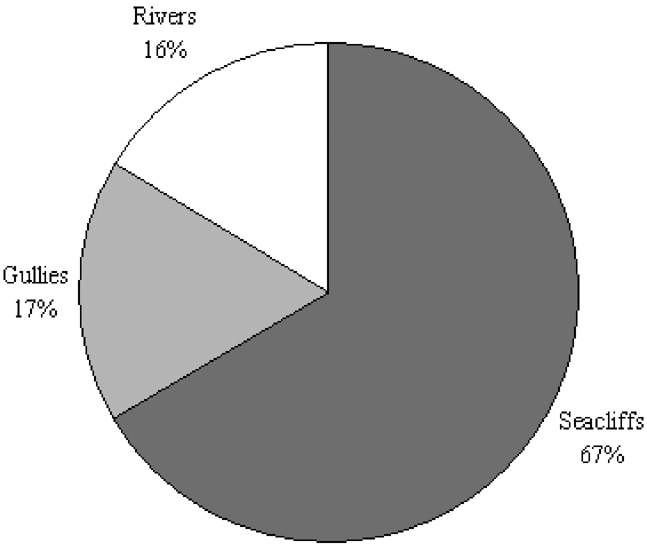

Figure 10. Estimated percentage of beach-sediment contributions to the Oceanside Littoral Cell for the study area between April 1998 and April 2004 (a statistically dry period).

Figure 11 shows the percentage of beach-sediment contributions based on EMERY and KUHN'S (1982) profile classification (Figure 3) from Table 1. This figure shows that areas controlled by subaerial erosion produced the majority of the

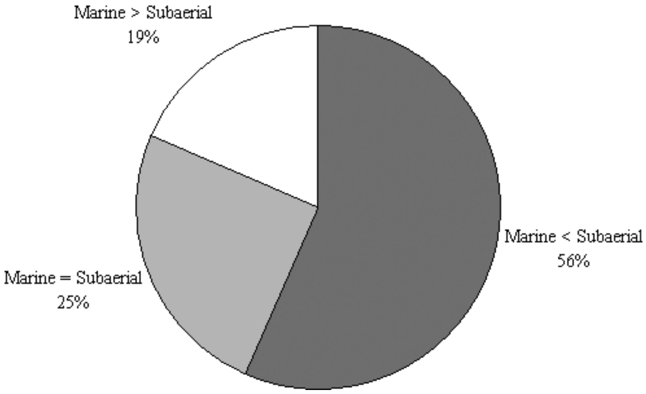

Figure 11. Seacliff beach-sediment contributions classified by the dominating section erosional process for the study area between April 1998 and April 2004. This figure is based on profile classification (Figure 3) and designation from Emery and Kuhn (1982).

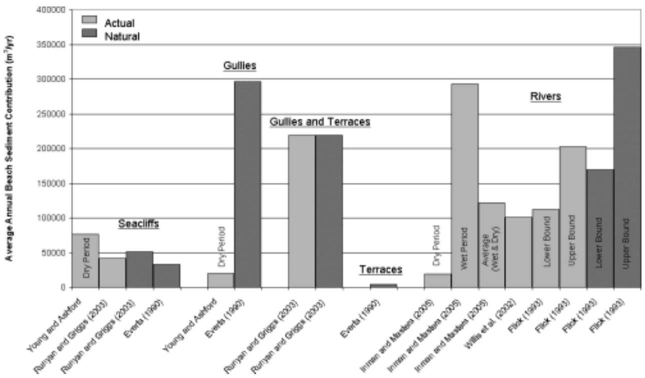

Figure 12. Comparison of average annual beach-sediment contributions to the Oceanside Littoral Cell from previous studies compared with this study. Values computed in this study represent the short-term 6-year dry period, whereas other studies represent long-term averages.

beach sediment. It should be noted that even though subaerial processes dominated, marine erosion is important in controlling the rate of erosion. If wave action were not present, seacliff material would not be removed from the base of the cliffs, the cliffs would become relatively stable, and thereby the retreat rate would be reduced. This conclusion is supported by the fact that the rates of seacliff retreat for the Dana Point and San Clemente sections were two of the three lowest of the sections evaluated. These sections are removed from wave action, and therefore only subaerial processes are acting in these locations.

Figure 12 compares the average annual beach-sediment yields from various sources calculated in this study and previous studies. During this study period, seacliffs yielded 76,900 m^3/yr of beach sediment. This is significantly higher than the previously estimated rates of 32,000 m^3/yr (EVERTS, 1990) and 42,000 m^3/yr (RUNYAN and GRIGGS, 2003). Given the dry period of this study, these results suggest that seacliff beach-sediment contributions may be higher than previously thought. Gullies yielded 20,000 m^3/yr of sediment during the study period, which is significantly lower than rates reported in other studies. This is likely because of the episodic nature of gullying. Robinson's study covered a time period during which several severe gully events occurred as a result of altered drainage patterns associated with the construction of coastal highways. These large gully events did not compare in magnitude to any gully events in this study. We suggest that average annual gully beach-sediment contributions reported in previous studies should be reconsidered for future studies unless more severe gully events occur in the future.

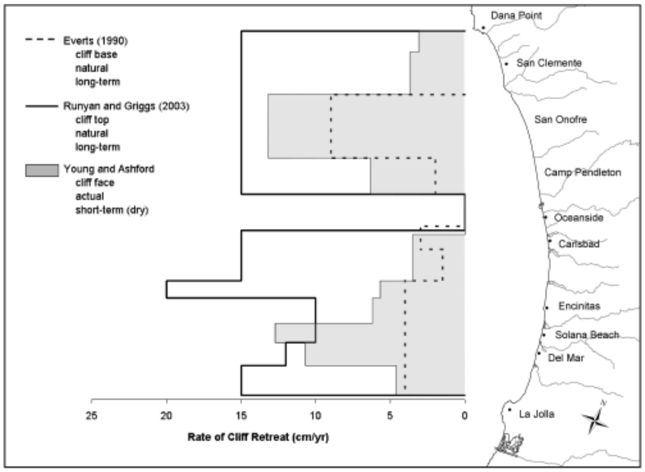

Figure 13. Comparison of average annual seacliff retreat rates from previous studies used to calculated average annual seacliff beach-sediment contributions to the Oceanside Littoral Cell and retreat rates back-calculated in this study.

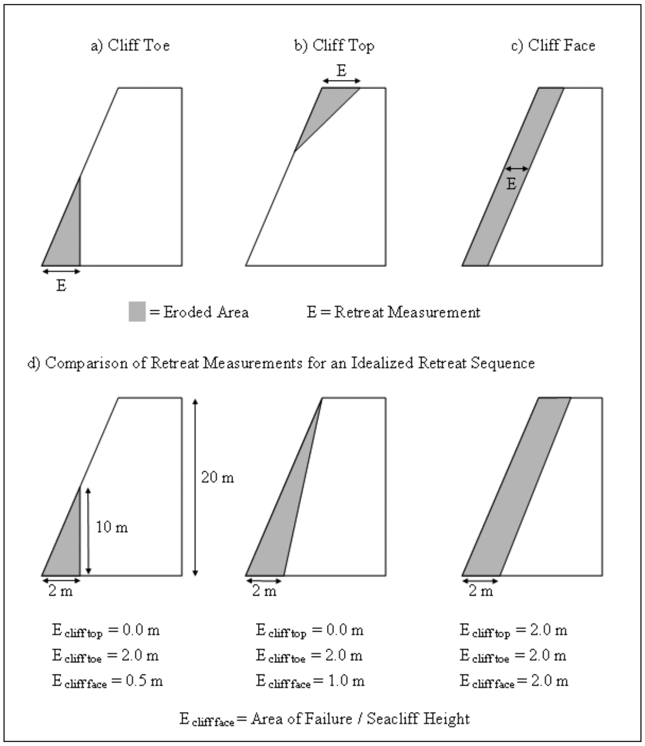

Figure 14. (a, b, c) Comparison of the techniques used to measure cliff retreat. (d) Comparison of how retreat measurements vary with an idealized erosion sequence. Note: using the average cliff face method removes some of the episodicity of the measured retreat.

The seacliff face retreat rates ranged from 3.1 to 13.2 cm/yr, with a weighted cell average of 8.0 cm/yr. These rates are at the low end of long-term rates ranging from 1.5 to 43.0 cm/yr (BENUMOF and GRIGGS, 1999; EVERTS, 1990; RUNYAN and GRIGGS, 2003). A comparison of seacliff retreat rates for the Oceanside Littoral Cell is shown in Figure 13. Note that the long-term rates from previous studies represent the natural rate of cliff top (RUNYAN and GRIGGS, 2003) and cliff toe (EVERTS, 1990) retreat, whereas the rates calculated in this study represent the short-term actual cliff face retreat in the partially armored condition. Figure 14 shows how different studies measure the retreat of a seacliff and a comparison of the measured retreat for an idealized erosion sequence. This figure shows how it is critical to understand where the retreat is being measured and why retreat rates may not be directly comparable. This figure also shows how using the cliff face retreat measurement as described in this study averages the failure area over the cliff face, thereby removing some of the episodic nature of retreat measurements. Comparison of the retreat measurements through the retreat cycle shows that the three measurement techniques are not equal until the erosion cycle has been completed. It should be noted that the retreat rates calculated in this study were averaged over the entire cliff section, including armored areas. Therefore, the natural rate of retreat would be significantly higher in heavily armored sections. The relatively low rates found in this study are likely because of the partially armored condition and the dry climate study period.

A comparison of the average annual seacliff beach-sediment yields and cliff retreat rates from this study, EVERTS (1990), and RUNYAN and GRIGGS (2003) reveals a discrepancy. Because all of these studies used the same general form of Equation (1), the retreat rates and beach-sediment volumes should correlate in size with one another. This is not the case; the beach-sediment volume calculated in this study is larger than that reported by RUNYAN and GRIGGS (2003), yet the retreat rate of this study is smaller than RUNYAN and GRIGGS (2003). The main reason for this discrepancy comes from the significant differences in cliff height used by this study and RUNYAN and GRIGGS (2003).

Given the relatively short study time period and the episodic nature of cliff failures, it is difficult to make any long-term conclusions. The seacliff and gully beach-sediment contributions could be viewed as lower bounds, given the relatively dry climate of the study period. Nevertheless, the results of this study indicate that seacliff beach-sediment contributions are a significant beach-sand source in the Oceanside Littoral Cell. This study also suggests that the relative seacliff beach-sand contribution may be significantly higher because of a possible overestimation of annual gully beach-sand contributions for current conditions.

This study also demonstrates that airborne LIDAR analysis can be used to quantify seacliff and gully beach-sediment contributions on a large scale. Further research should be conducted to quantify volumetric changes during wet periods. A comparison of dry and wet time periods could be used to quantify the episodic nature of seacliff retreat. Additional research should also be conducted to more accurately quantify the effects of marine versus subaerial erosion processes. Now that a baseline for the Oceanside Littoral Cell has been established, future airborne LIDAR scanning can be used to evaluate the longer term rates of seacliff erosion.

ACKNOWLEDGMENTS

This publication was supported in part by the National Sea Grant College Program of the US Department of Commerce's National Oceanic and Atmospheric Administration under NOAA Grant NA06RG0142, project R/OE-37, through the California Sea Grant College Program, and in part by the California State Resources Agency. Additional support was provided by the University of California, Coastal Environmental Quality Initiative Program, under Award 04-T-CEQI-06-0046. In addition, the authors would like to acknowledge and sincerely thank Richard Seymour, Robert Guza, Julie Thomas, and Randy Bucciarelli of the Southern California Beach Processes Study, operated by the Scripps Institution of Oceanography under the sponsorship of the US Army Corps of Engineers and the California Department of Boating and Waterways, for providing the 2004 LIDAR data set. Without their collaboration, this research effort would not have been possible.

LITERATURE CITED

ATM (AIRBORNE TOPOGRAPHIC MAPPER), 1998. West Coast LIDAR. Partners: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center, the NASA Wallops Flight Facility, the U. S. Geological Survey (USGS) Center for Coastal and Regional Marine Geology, and the NOAA Aircraft Operations Center.

BENUMOF, B.T. and GRIGGS, G.B., 1999. The relationship between seacliff erosion rates, cliff material properties, and physical processes. *Shore and Beach,* 67(4), 29–41.

BEST, T.C. and GRIGGS, G. B., 1991. A sediment budget for the Santa Cruz littoral cell. *Society of Economic Paleontologists and Mineralogists,* Special Publication No. 46, pp. 35–50.

BOWEN, A.J. and INMAN, D.L., 1966. Budget of Littoral Sands in the Vicinity of Point Arguello, California. U.S. Army Coastal Engineering Research Center.

BROWNLIE, W.R. and TAYLOR, B.D., 1981. Sediment Management for the Southern California Mountains, Coastal Plains, and Shoreline, Part C: Coastal Sediment Delivery by Major Rivers in Southern California. California Institute of Technology, Environmental Quality Lab Report No. 17-C, February 1981.

DIENER, B.G, 2000. Sand contribution from bluff recession between Point Conception and Santa Barbara, California. *Shore and Beach,* 68(2), 7–14.

EMERY, K.O. and KUHN, G.G., 1982. Sea cliffs: their processes, profiles, and classification. *Geological Society of America Bulletin,* 93, 644–654.

EVERTS, C.H., 1990. Sediment budget report, Oceanside Littoral Cell. Coast of California Storm and Tidal Wave Study 90–2, U.S. Army Corps of Engineers, Los Angeles District. 110p.

FEDERAL GEOGRPAHIC DATA COMMITTEE, 1998. Geospatial positioning accuracy standards. FGDC-STD-007.3–1998, 28p.

FLICK, R.E., 1993. The myth and reality of southern California beaches. *Shore and Beach,* 61(3), 3–13.

GRIGGS, G.B., 1987. The production, transport, and delivery of coarse-grained sediment by California's coastal streams. *Proceedings of Coastal Sediments '87,* Vol. 2. New York: American Society of Civil Engineers, pp. 1825–1838.

GRIGGS, G.B. and SAVOY, L., (ed.), 1985. *Living with the California Coast.* Durham, North Carolina: Duke University Press, 393p.

HAAS, J.K., 2005. Grain Size and Mineralogical Characteristics of Beach Sand in the Oceanside Littoral Cell: Implications of Sediment Provenance. San Diego, California: University of California San Diego, Master's thesis, 41p.

HAPKE, C.J., 2005. Estimation of regional material yield from coastal landslides based on historical digital terrain modeling. *Earth Surfaces Processes and Landforms,* 30(6), 679–697.

HICKS, D.M. 1985. Sand Dispersion from an Ephemeral Delta on a Wave-Dominated Coast. Ph.D. Dissertation, University of California, Santa Cruz, 210p.

INMAN, D.L. and BRUSH, B.M., 1973. The coastal challenge, *Science,* 181, 20–32.

INMAN, D.L. and FRAUTSCHY, J.D., 1966. Littoral processes and the development of shorelines. Proceedings, Coastal Engineering Specialty Conference (ASCE, Santa Barbara, California), pp. 511–536.

INMAN, D.L. and JENKINS, S.A., 1999. Climate change and the episodicity of sediment flux of small California rivers. *Journal of Geology,* volume 107, p 251–270.

Inman, D.L. and Masters, P.M., 2005. Living with Coastal Change. Scripps Institution of Oceanography, University of California, San Diego. http://coastalchange.ucsd.edu (accessed August 30, 2005).

IPCC (Intergovernmental Panel on Climate Change), Working group I, 2001. *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the IPCC.* Cambridge, UK: Cambridge University Press, 873p.

Kennedy, M.P., 1975. Geology of the San Diego metropolitan area, western area. California Division of Mines and Geology Bulletin 200, 56p.

Kuhn, J.P. and Shepard, F.P., 1984. *Sea Cliffs, Beaches, and Coastal Valleys of San Diego County: Some Amazing Histories and Some Horrifying Implications.* Berkeley, California: University of California Press, 193p.

Miller, M., 2005. *The Weather Guide, A Weather Information Companion for the Forecast Area of the National Weather Service in San Diego, 3rd Edition.* San Diego: National Weather Service, 116p.

Moore, L.J.; Benumof, B.T., and Griggs, G.B., 1999. Coastal erosion hazards in Santa Cruz and San Diego Counties, California. *Journal of Coastal Research,* Special Issue No. 28, pp. 121–139.

NOAA (National Oceanic and Atmospheric Administration), 2004. Coastal Services Center. http://www.csc.noaa.gov

Robinson, B.A., 1988. Coastal cliff sediments—San Diego region, Dana Point to the Mexican border (1887–1947). Coast of California Storm and Tidal Wave Study 88–8. U.S. Army Corps of Engineers, Los Angeles District, 275p.

Runyan, K. and Griggs, G.B., 2003. The effect of armoring seacliffs on the natural sand supply to the beaches of California. *Journal of Coastal Research,* 19(2), 336–347.

Sallenger, A.H.; Krabill, W.B.; Swift, R.N.; Brock, J.; List, J.; Hansen, M.; Holman, R.A.; Manizade, S.; Sontag, J.; Meredith, A.; Morgan, K.; Yunkel, J.K.; Frederick, E.B., and Stockdon, H., 2003. Evaluation of airborne topographic LIDAR for quantifying beach changes. *Journal of Coastal Research,* 19(1), 125–133.

USACE-LAD (U. S. Army Corps of Engineers—Los Angeles District), 1984. Geomorphology framework report Dana Point to the Mexican border. Coast of California Storm and Tidal Wave Study 84–4, 101p.

USACE-LAD, 2003. Encinitas and Solana Beach Shoreline Feasibility Study, San Diego County. Appendix C, 75p.

Western Regional Climate Center, 2005. http://www.wrcc.dri.edu

Willis, C.M.; Sherman, D., and Lockwood, B. 2002. Chapter 7: Impediments to fluvial Delivery of Sediment to the Shoreline. In: Coyne, M. and Sterrett, K. (eds.), *California Beach Restoration Study.* Sacramento, California: California Boating and Waterways and State Coastal Conservancy, 280p.

Zhang, K.; Whitman, D.; Leatherman, S., and Robertson, W., 2005. Quantification of beach change caused by hurricane Floyd along Florida's Atlantic coast using airborne laser surveys. *Journal of Coastal Research.* 21(1), 123–134.