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Coastal Sediment Budgets and the Littoral Cutoff Diameter: A Grain Size Threshold for Quantifying Active Sediment Inputs

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ABSTRACT

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The use of coastal sediment budgets has garnered wide acceptance since its inception nearly 40 years ago. Since then, many researchers have used sediment budgets to quantify littoral transport rates and understand coastal processes on diverse coastlines including the high-energy Pacific coast of North America, the Black Sea, the Nile Delta and beyond. Here, we suggest further improvement on an already successful conceptual tool by questioning the broad definition of sand set forth by the classic Wentworth grain size scale (63–2000 microns) that is often used in quantifying coastal sediment budget inputs from sources such as coastal-draining rivers and eroding sea cliffs. A smaller range of sediment sizes is found on many beaches in California. This range is defined by a minimum grain size threshold, termed the littoral cutoff diameter. Sediment contributed to the littoral system that is smaller than this threshold, even if defined as sand by the Wentworth scale, may not remain on the beach in any significant quantity. The littoral cutoff diameter ranges from 88 to 180 microns on the California beaches studied herein, and results from a variety of locations show that yearly littoral sediment flux from coastal-draining rivers and eroding sea cliffs can be overestimated by 16–300% percent if the littoral cutoff diameter is not considered. The presence of the littoral cutoff diameter suggests that quantifying sediment inputs within the context of preexisting littoral sediments is of first-order importance when constructing sediment budgets in California and in other analogous coastal environments.

ADDITIONAL INDEX WORDS: *Littoral cell, Merced Formation, Wentworth scale, grain size analysis, California, sediment budget.*

INTRODUCTION

In California, sediment budgets and littoral cells form the framework on which we base our understanding of sediment transport along the shoreline (GRIGGS, 1987). Sediment budgets are, in effect, a means of applying Lavoisier's Law of Conservation of Mass to littoral sediments, in which the time rate of change in the volume of littoral sediments along a given stretch of shoreline relies on the rate that sediments are both contributed to and lost from the littoral system (BOWEN and INMAN, 1966; KOMAR, 1996). The finite littoral system in which a sediment budget is applied is called a littoral cell or beach compartment and is enclosed by discrete physical boundaries such as a rocky headland or submarine canyon. These boundaries inhibit the continuous alongshore movement of sediment into and out of the cell and form a theoretically closed system. Within a cell, various sediment inputs, primarily from coastal streams and eroding coastal bluffs, can be balanced with sediment outputs, such as eolian losses and offshore transport, to create a sediment budget and an estimate of annual longshore transport rates. Quantifying littoral sediment inputs and outputs in this manner allows us to gain insight into the importance of the individual sediment sources and sinks that affect the stability of our beaches, and in turn, provide useful answers for agencies and policymakers managing the coastal environment.

BOWEN and INMAN (1966) pioneered the modern-day littoral sediment budget and first advocated the concept of a littoral cell through a study in Santa Barbara, California, where they quantified the flux of sand-sized sediment entering and exiting the littoral system through various geomorphic processes such as sea cliff erosion, fluvial discharge, and eolian transport. Since then, their methodology has been duplicated extensively and applied to a great variety of coastlines, including those of Japan (SUNAMURA and HORIKAWA, 1977), Great Britain (COOPER and PETHICK, 2005), the Black Sea (GIOSAN *et al.,* 1999), Egypt (SAIED and TSANIS, 2005), France (BATTIAU-QUENEY *et al.,* 2003), Holland (VANRIJN, 1997), and most comprehensively along the Atlantic and Pacific coasts of the United States (BEST and GRIGGS, 1991; KANA, 1995; PIERCE, 1969; ROSATI, 2005).

All of these sediment budgets are fundamentally similar in

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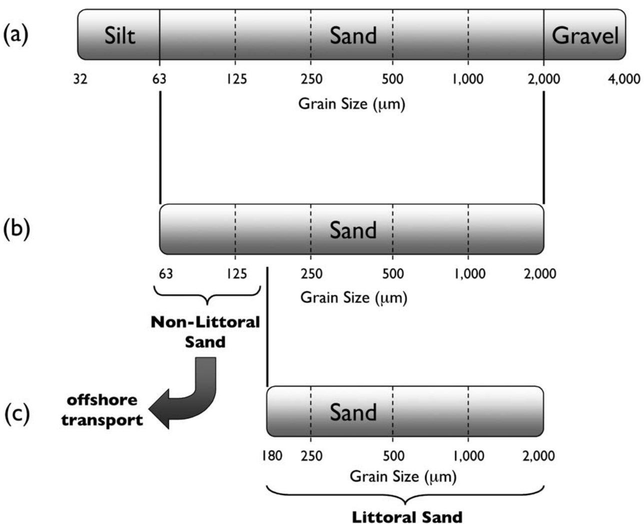

Figure 1. Schematic depicting the application of the littoral cutoff diameter (LCD). Scene *a* is a hypothetical sediment source consisting of a wide range of grain sizes. Scene *b* shows the sand fraction of the sediment source as determined by the Wentworth scale and as often used in sediment budget studies to define littoral inputs. However, the entire spectrum of sand sizes shown in scene *b* will not necessarily be present on a given beach due to the local or regional hydraulic processes acting on the sediment. Thus it is important to determine an LCD for which sediment is of sufficient size to contribute as a littoral sediment input for a given area (scene *c*).

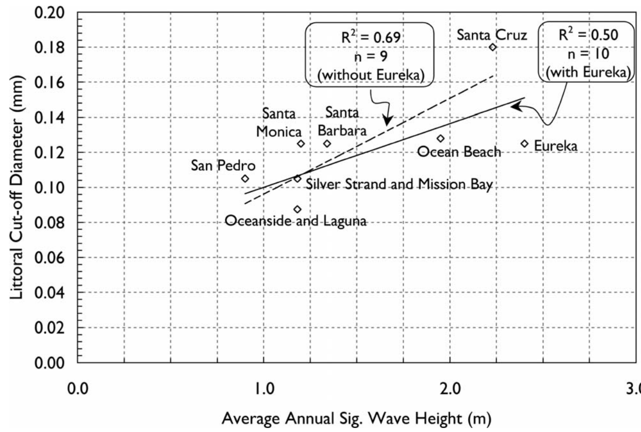

Figure 2. Approximate relationships between mean annual significant wave height and the littoral cutoff diameter (LCD) in California. It should be noted that significant wave heights determined here from historical wave buoy data (NOAA, 2006) are based on open-ocean measurements and may not fully represent wave conditions at a given beach. All LCD values are from Patsch and Griggs, 2005 except Ocean Beach (this study), Santa Barbara (Runyan and Griggs, 2003), and Santa Cruz (Best and Griggs, 1991).

approach and purpose, and many share an additional commonality in that the grain size of littoral inputs has not been adequately considered within the context of the sediment sizes already present in the littoral cell or study area. Typically, the amount of material contributed to a littoral cell from a given active sediment source, such as eroding sea cliffs or discharge from coastal rivers and streams, has been broadly restricted to that of sand-sized material, *i.e.,* sediment defined by the WENTWORTH (1922) grain size scale to be between 63 and 2000 μm in diameter. BOWEN and INMAN (1966) used this grain size range in their original sediment budget; however, a number of more recent studies performed along the high-energy California coast (*e.g.,* BEST and GRIGGS, 1991; EITTREIM *et al.,* 2002; HICKS, 1985; RUNYAN and GRIGGS, 2003) have revealed that, on many beaches, only a relatively small window of sand-sized sediment exists. It follows that defining active littoral inputs as any sand-sized material between 63 and 2000 μm can lead to significant budget overestimations, and it is proposed here that evaluating the grain size of sediment inputs within the context of preexisting littoral sediments is of first-order importance when constructing sediment budgets in California and in other analogous coastal environments.

GLOGOCZOWSKI and WILDE (1971) and HICKS (1985; see also HICKS and INMAN, 1987) were the first to recognize that a minimum sediment grain size threshold, termed by HICKS (1985) as the littoral cutoff diameter (LCD; Figure 1), exists along the wave-dominated California coast. The LCD can be defined as a grain size threshold below which sediment will not remain on a given beach in any significant quantity (HICKS, 1985). In California, the LCD is thought to be a function of wave energy (Figure 2), and sediment finer than the LCD delivered to a beach from a particular littoral input will likely be easily entrained, suspended, and deposited offshore as a permanent loss to the beach system (EITTREIM *et al.,* 2002). HICKS (1985) found that, after sieving nearshore, foreshore, and swash sediment samples taken from the shoreline adjacent to the San Lorenzo River in Santa Cruz, California, the grain size below which sediment was not found in large quantities, the LCD, in the littoral zone was 180 μm. Comparing this with suspended sediment and bedload samples collected from the San Lorenzo River, 96% of the bedload and only 21% of the suspended sediment load was equal to or coarser than 180 μm, corresponding to 28% of the total sediment load from the San Lorenzo River. Therefore, although fluvial discharge from the San Lorenzo River acts a considerable coastal sediment source, only 28% is of sufficient size to contribute to the littoral system and also to the littoral sediment budget.

Although the LCD has been similarly applied in other recent coastal sediment budget studies in California (*e.g.,* BEST and GRIGGS, 1991; PATSCH and GRIGGS, 2005; RUNYAN and GRIGGS, 2003; YOUNG and ASHFORD, 2006), the concept has not been the primary focus of any investigation and has not been considered by researchers outside of California. The aim of this paper is to put forward the LCD as an important variable that bears regional consideration when budgeting littoral sediments.

THE WENTWORTH SCALE AND CROSS-SHORE SEDIMENT SORTING

In devising his classic and widely used scale of sediment grain sizes and terminology, WENTWORTH (1922) categorized the observed grain size continuum of naturally occurring granular sediments. The resulting scale and its size classes are largely based on an amalgamation of 28 written opinions, concerned primarily with the semantics of sediment terminology, solicited by Wentworth from scientists at the U.S. Geological Survey (USGS). In addition to these responses, as well as previously published classification schemes, WENTWORTH (1922) also acknowledged several factors relating to the assignment of discrete size classes to his grain size scale. First, the growing acceptance of sieve analysis in which sediment samples are passed through sieve openings successively aligned at a ratio of two (UDDEN, 1914) imparted structure to the size class scale and allowed Wentworth to construct a similar logarithmic series in which the ratio, arbitrarily starting at 1 mm, of each size class to the next is also two (see Figure 1). Such a scheme recognizes the necessity that the differences between two successive size classes should be greater for the large sizes than for the small, as a change of 1 inch in the diameter of 10 inch cobbles is of the same magnitude as a change of 1/10 inch in the size of 1 inch pebbles, and also that a scale representing such a large array of grain sizes can only be appropriately accommodated by a geometric or logarithmic progression (WENTWORTH, 1922). Second, and perhaps more importantly, the logarithmic classification scheme makes the size classes "fall into equal units on the graph" (WENTWORTH, 1922), thus affording a simple means of interpretation and quick visual analysis.

On the other hand, although intuitively practical, the classification scheme gives no weight to sediment composition:

> The present scheme of grade terms is, accordingly, just what its name implies—a series of names for clastic fragments of different sizes . . . The names applied to the different grades carry no lithologic, mineralogic, or chemical significance so far as the present scheme is concerned. (WENTWORTH, 1922, p. 379)

Consequently, it seems that the size classes relevant to this discussion, those of sand-sized sediment between 63 and 2000 μm, are somewhat arbitrarily defined on the grounds described above and carry little hydraulic or geomorphic distinction (RUNYAN and GRIGGS, 2003). Generally applying this range to delineate beach-type material for a given sediment input presupposes that the hydraulic or geomorphic processes actively sorting the sediment will function according to the Wentworth scale and selectively remove any contributed sediment finer than 63 μm (silt) or coarser than 2000 μm (gravel). Instead, we suggest that the amount of sediment of sufficient size to contribute to a littoral system should not be determined solely by the Wentworth scale, but from first-hand analysis of the sand fraction present on the beach resulting from the local or regional geologic, oceanographic, and hydraulic processes acting within the area under consideration. This is not to say that the Wentworth scale is altogether inapplicable with respect to sediment budgets, however. The maximum grain size threshold used herein to quantify littoral sediment inputs is 2000 μm, or the Wentworth scale's break between coarse sand and gravel. Because annual gravel inputs are generally small in California, and annual fine sand inputs, on the other hand, can total up to several hundred thousand cubic meters from a single sediment source, the largest potential source of sediment budget error can result from inaccurately quantifying fine sediment inputs. For this reason, the default 2000-μm maximum threshold works reasonably well, and it is more important to establish a minimum LCD to determine whether fine sand being delivered to the coastline is littoral-type (*i.e.,* coarser than the LCD). In areas with large amounts of gravel inputs or those with predominantly shingle beaches, however, the 2000-μm threshold should be reevaluated and a maximum, as well as minimum, LCD should be established.

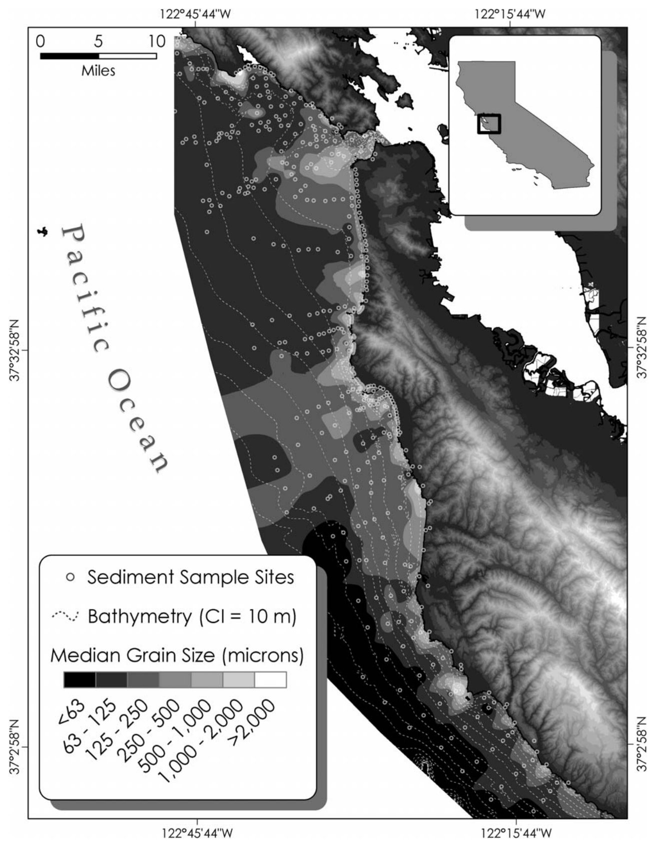

Figure 3. Sediment classification map showing coastal and shelf sediment grain sizes along the central California coast. Values shown are median grain sizes in microns (μm) and are classified according to size classes defined by Wentworth (1922). The bathymetry contour interval (CI) is 10 m.

A regional demonstration of the LCD concept can be seen in Figure 3. A series of grain size surveys (LEE and GLOGOCZOWSKI, 1971; LEE, YANCEY, and WILDE, 1970; MOORE, 1965; SAYLES, 1965) completed along the central California coast comprising a total of nearly 600 sediment samples taken from the beach and up to 30 km offshore were scanned, digitized, and interpolated in a geographical information systems (GIS) environment. The interpolated values shown on the map in Figure 3 are median grain sizes in microns (μm) and are classified by sediment size according to the Wentworth scale. A general offshore fining trend is apparent, and the majority of medium to coarse sand (500–2000 μm) is located closer to shore in depths less than ~20 m, while finer sand (63–500 μm) and silt (28–63 μm) are found in progressively deeper water farther offshore. The sediments are terrigenous in nature and are derived primarily from fluvial discharge by rivers and streams draining the nearby Santa Cruz Mountains and also from sea cliff erosion (Best and Griggs, 1991; Edwards, 2002; Limber, 2005). Thus, these terrigenous sediments are sorted in a cross-shore pattern in which finer sediments, due to their increased settling times and increased likelihood of being resuspended by surface waves (Eittreim *et al.,* 2002), are transported in a net offshore direction and deposited in the deeper and calmer waters of the inner and midshelf region (Lewis *et al.,* 2002; Xu, Noble, and Eittreim, 2002). Coarse sediment is left in the high-energy littoral zone closer to the original area of deposition, where, at a size roughly proportional to wave energy (Figure 2), it is entrained in littoral drift (Eittreim *et al.,* 2002; Lewis *et al.,* 2002) and comprises the bulk of beach-building material. Best and Griggs (1991) determined a regional LCD of 180 μm for the area shown in Figure 3, wherein sediment finer than this threshold is deposited seaward of the littoral zone.

Similar offshore fining has been observed on various other coastlines (Fox, Ladd, and Martin, 1966; Horn, 1992; Ingle, 1966; Niedoroda *et al.,* 1985; Stauble and Cialone, 1997), and there seems to be little doubt that as water depth increases in the nearshore and offshore zones, grain size generally decreases. In the nearshore zone, numerous researchers have modeled the critical size threshold for bedload sediment movement under oscillatory waves (*e.g.,* Green, 1999; Horn, 1992; Jago and Barusseau, 1981; Komar and Miller, 1975). Such models shed light on the variables influencing the establishment of LCDs in the littoral zone and indicate that it is a complex process dependent on several interrelated variables including wave height, period, water depth, nearbed wave orbital velocity, and wave orbital diameter, among others. The LCD is thus a concept that has been extensively considered in a theoretical sense, but has not been widely applied in the field with regard to sediment budgets.

DEFINING AND SAMPLING THE LITTORAL CUTOFF DIAMETER (LCD)

Since its inception, the LCD has been determined in a number of ways. Hicks (1985) defined it as the average mean grain size of several swash, foreshore, and nearshore samples minus one standard deviation. This method approximates the fine tail of a well-sorted log-normal grain size distribution and represents an LCD at which approximately 84% of the sample is coarser and 16% is finer (Hicks, 1985). In subsequent studies, the LCD has been more stringently defined. Best and Griggs (1991), while performing a sediment budget for the Santa Cruz, California, littoral cell, adapted the method of Hicks (1985) by taking the average D_{10} value (the grain size for which 90% of a sample is coarser and 10% is finer based on sieve analysis) of 40 regional beach, swash, and nearshore samples and then subtracting one standard deviation from that number to arrive at an LCD of 180 μm. In a later study quantifying littoral inputs from sea cliff erosion in Santa Barbara, California, Runyan and Griggs (2003) reached an LCD of 125 μm by sieving beach samples and taking the grain size for which 95–98% of the sediment in all samples was coarser. Limber (2005) followed the methodology of Best and Griggs (1991) to calculate an LCD of ~125 μm for Ocean Beach, San Francisco, and that is the method used in the San Francisco case study presented herein.

Sampling littoral sediment to determine the LCD for an area is a relatively straightforward procedure, although it requires several considerations. The aim is to establish a minimum grain size threshold, so a simple way to obtain a representative size distribution of the littoral sediment in a certain area is to sample the beach face during summertime, when the grain size is at a yearly minimum. As a result, the LCD will not be overestimated, and in addition, samples of an accreting summertime beach face are approximately representative of the beach system as a whole (Hicks, 1985; Inman, 1953). It is also important to sample thoroughly, as grain size can vary alongshore because of local variations in wave energy. Bascom (1951) found this relationship to be true along the coast of Half Moon Bay, California, where prior to breakwater construction, a large headland initially sheltered the north part of the bay from dominant northwesterly swell while the south part of the bay was fully exposed to incoming wave energy. Beach profiles taken along the entirety of the bay showed a distinct southward coarsening trend coincident with increasing wave energy, where grain size within the sheltered part of the bay averaged 170 μm and progressively increased to 650 μm to the south where wave energy was at a maximum. Mean grain size (and likely the LCD) varied not only on a regional basis as a result of prevailing oceanographic and geomorphic processes, but also in response to more localized features. It is important to sample thoroughly to account for these changes.

Especially for large study areas, manually sieving a multitude of samples to determine the LCD can be overly time consuming. In recognition of this, Rubin (2004) has developed a simple spatial autocorrelation algorithm for analyzing digital images of sediment that offers significant promise for efficiently calculating grain size statistics (see Rubin, 2004 for a more in-depth explanation of this process). The algorithm can be run using MATLAB software at up to 100 times faster than traditional sieving methods (Rubin, 2004), and sediment imagery can be obtained with a standard digital camera. Furthermore, the USGS has manufactured and patented a handheld waterproof camera casing used to capture swash and foreshore sediment *in situ.* The apparatus is known as the eyeball camera, and in conjunction with the spatial autocorrelation algorithm, it has been used successfully to monitor beach grain sizes (Chezar and Rubin, 2004; P. Barnard, USGS, personal communication) and to calculate the LCD on Ocean Beach, San Francisco (Limber, 2005). The relative ease and speed of this technique makes it well suited for regional littoral cell analyses and for densely sampling littoral sediment as a means to calculate LCDs.

Several possible methods of calculating and sampling the LCD have been outlined above, but regardless of the method

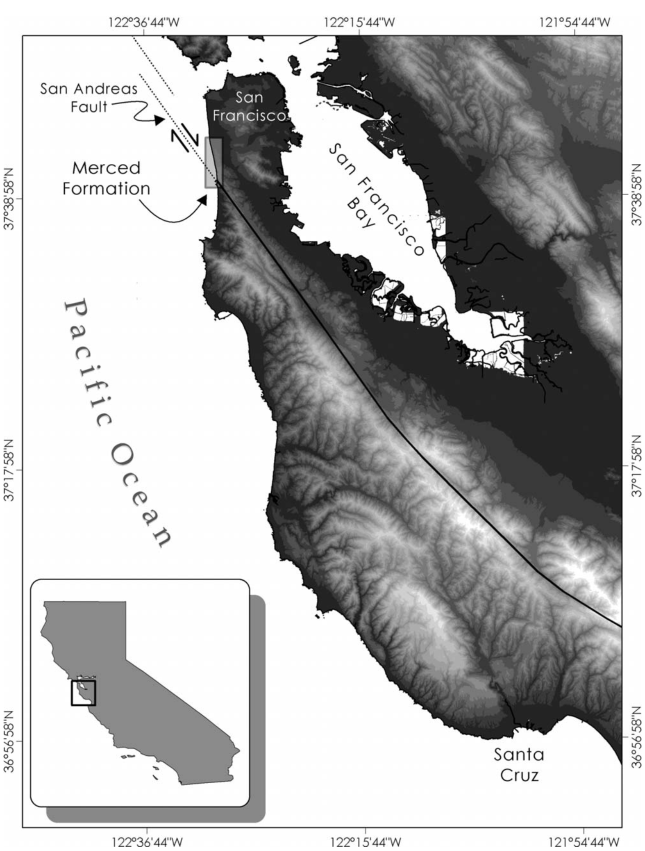

Figure 4. Map of the central California coastline showing the location of the Merced Formation study area.

Figure 5. Standing on the San Andreas Fault looking north along the Merced Formation toward San Francisco.

used, defining a minimum grain size threshold is a useful way to more accurately quantify littoral inputs and gain a more thorough understanding of the site-specific processes acting to sort and distribute sediment in the littoral zone. In California, not applying the LCD can lead to significant overestimations of littoral inputs, as shown in the case studies presented below. The first, a localized study near San Francisco, provides a thorough discussion of the LCD in quantifying a single, but complex, active sediment input and its potential effects on the local sediment budget. The remaining case studies, summarized from previous work, operate on a more regional scale and demonstrate the applicability and implications of the LCD on sediment budgets in the Eureka littoral cell in northern California, as well as multiple littoral cells in southern California. The case studies will illustrate potential applications of the LCD with regard to coastal sediment budgets and demonstrate the possible discrepancy between quantifying littoral inputs according to the Wentworth scale using sand-sized material (63–2000 μm) and using the LCD.

CASE STUDY I: THE MERCED FORMATION, SAN FRANCISCO, CALIFORNIA

The Merced Formation is a 1750-m-thick Plio-Pleistocene succession of paleo-beach and shelf sediments that was originally deposited at or near sea level (Carter *et al.,* 2002; Clifton and Hunter, 1987). This unit, adjacent to the San Andreas Fault, has experienced relatively rapid uplift and deformation (Wakabayashi, Hengesh, and Sawyer, 2004), forming high (10–200 m) friable sea cliffs along 6 km of coastline just south of San Francisco (Figures 4 and 5; Clifton, Hunter, and Gardner, 1988). The strata are cyclical in nature (Carter *et al.,* 2002) and can each be ascribed to one of eight recurring dominant depositional environments or facies, including continental shelf, nearshore, foreshore, backshore, eolian, alluvial, embayment/estuarine, and paleosol (Clifton, Hunter, and Gardner, 1988).

Erosion of the sand-rich Merced Formation has long been thought of as an important local and regional littoral sediment source; however, this has not been quantitatively assessed. Best and Griggs (1991) postulated that it comprises a significant regional sediment source, and the USGS is currently conducting a long-term study at Ocean Beach, San Francisco (Barnard and Hanes, 2005; USGS Ocean Beach website: http://walrus.wr.usgs.gov/coastal_processes), in which it will be interesting to note how input from the Merced Formation fits into local sediment transport processes. Also, because it contains a plethora of sediment sizes ranging from silt to gravel, the Merced Formation serves as an ideal site to both quantify an unknown and possibly significant littoral sediment input and to demonstrate the importance and applicability of the LCD.

Methods

A simple equation can be used to calculate the littoral contribution from sea cliff erosion (Q_{cliff}):

$$Q_{\mathrm{cliff}} = (A \times \%\mathrm{CD})dx/dt \qquad (1)$$

where A is the surface area of the cliff in m² (alongshore length × height), %CD is the percentage of cliff material with a grain size equal to or greater than the littoral cutoff di-

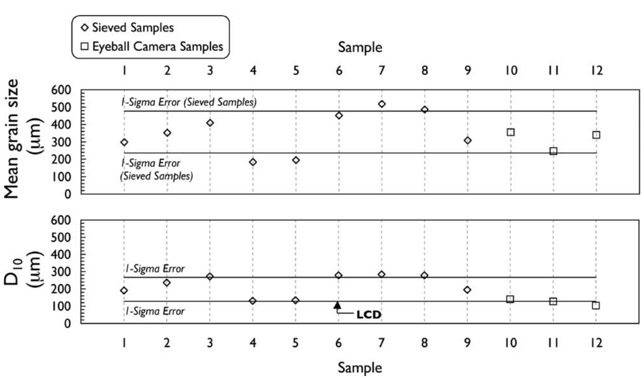

Figure 6. Top plot shows the mean grain size of beach samples processed by sieving and analysis with the eyeball camera. The 1-σ error boundaries illustrate that the eyeball camera samples all fall within one standard deviation of the sieved samples. The bottom plot shows the D_{10} grain size values for all beach samples, and the bottom 1-σ error boundary denotes the LCD of ~125 μm or 3 ϕ.

ameter, and *dx/dt* is the long-term erosion rate in meters per year. Calculating *A* is straightforward and can be done accurately using airborne light detection and ranging (LIDAR) data or with land-based surveying techniques. Calculating %CD requires two steps, one to sample and determine the grain size frequency of the sea cliff material and another to calculate the LCD. Finally, *dx/dt* can be calculated using historic vertical aerial photography or simply by using average rates from previous studies.

Before estimating Q_{cliff}, the LCD was calculated using a combination of sieve analysis and analysis performed by the eyeball camera and the spatial autocorrelation algorithm of RUBIN (2004). The inclusion of eyeball camera samples allowed comparison between results acquired through the digital spatial autocorrelation algorithm and traditional sieving methods. In addition, two sediment samples were both sieved and processed with the spatial autocorrelation algorithm to quantify the amount of error between each method. Each of these samples was first sieved and photographed three times with the eyeball camera, and then each image was processed with the spatial autocorrelation algorithm. An average of the three spatial autocorrelation results was used to compare with the sieved result for each sample.

The LCD was determined using the method of taking the average D_{10} value and subtracting one standard deviation from it of BEST and GRIGGS (1991). The resulting LCD of ~125 μm (3 ϕ) represents the grain size for which 93% of all samples were coarser and provides the framework for which Q_{cliff} estimates can be subsequently made.

Next, to begin estimating Q_{cliff}, two to five representative samples of each depositional facies were taken along the length of the Merced outcrop for which grain size analyses were performed. Because of its infrequency, the paleosol facies was excluded from this analysis, since it comprised only 0.5% of the entire formation. Additionally, the nearshore and foreshore facies were grouped together because of their sedimentological similarity and consistent adjacent stratigraphic position. Based on the two to five grain size analyses for each

Table 1. *The average percentage and error ranges of total sand and sand coarser than the LCD (>LCD) within each facies of the Merced Formation.*

Merced Formation Facies	Percentage Sand	Percentage Sand 1-σ Error	Percentage >LCD	Percentage >LCD 1-σ Error
Shelf	79	±8	11	±6
Nearshore/Foreshore	86	±2	80	±4
Backshore	97	±5	91	±9
Eolian	99	±0	96	±2
Alluvial	72	±1	68	±3
Embayment	71	±6	33	±20

facies, average cumulative frequency grain size distributions for each facies were derived from which the amount of littoral-type sediment coarser than the LCD could be calculated. Then, with the relative abundance of each depositional facies in the sea cliff from the scaled stratigraphic column completed by CLIFTON, HUNTER, and GARDNER (1988), Q_{cliff} could be estimated for the entire Merced Formation outcrop using a simple average weighted by facies abundance.

However, this method assumes that the Merced Formation outcrops exactly as drawn in the stratigraphic column, with dip remaining constant. In reality, this is not the case, as dip ranges from ~15 to 80 degrees. The more gently dipping strata outcrop for a proportionally greater distance alongshore than indicated in the stratigraphic column, and the steeper dipping strata are exposed in the sea cliff for shorter distances. To compensate for this, as well as for the cliff's wide range in height, the Merced Formation was divided into three sections based on the uniformity of height and dip angle, and Equation (1) was applied to each section separately and subsequently summed to calculate Q_{cliff} for the entire formation.

A long-term erosion rate of about 0.3 m y^{-1} was calculated for the Merced Formation by analyzing aerial photography spanning the past 70 years. This agrees well with erosion rates of approximately 1 ft y^{-1} calculated by previous researchers (GRIGGS and SAVOY, 1985; MOFFAT and NICHOL ENGINEERS, 1995).

Results

Mean and D_{10} beach grain sizes are shown in Figure 6. The mean grain size of the eyeball camera samples all fall within one standard deviation of the sieved samples, and a maximum of ~8% error can be attributed to the eyeball camera samples relative to the sieved samples based on the two sediment samples that were processed using both methods. In addition, a field test of the algorithm on 186 sediment samples obtained near the study area shows good agreement between grain sizes calculated by sieving and by digital methods (P. BARNARD, USGS, personal communication).

The LCD of ~125 μm, calculated by subtracting one standard deviation from the mean D_{10} grain size of all beach samples, is shown in Figure 6. Figure 7 shows the average cumulative frequency grain size distributions from each facies from the Merced Formation, along with a "littoral window" that brackets the sand-sized sediment coarser than the predetermined LCD of ~125 μm (3 ϕ). Using the grain size distributions, one can infer the total percentage of littoral-type sediment, or sediment coarser than the LCD, simply by noting at what percentage a distribution curve crosses the littoral window. Results of the amount of total sand-sized and littoral-type sediment for each facies are summarized in Table 1. All facies are predominantly made up of sand-sized material, since the Merced Formation consists largely of paleo-beach deposits; however, the shelf and embayment facies lack enough coarse sand to produce a significant amount of littoral-type material as defined by the LCD. Also listed in Table 1 are the 1-σ error ranges showing the variation caused from averaging a number of grain size distributions to produce one distribution for each facies. For the most part, this error is well under 20%. Values of possible overestimation if the LCD is not considered range from a minimum of 3% for the eolian facies to a maximum of 68% for the fine-grained shelf facies.

Finally, with the relative abundance of each facies within the Merced Formation, the LCD, and the erosion rate, Equation (1) can be applied to estimate the total Q_{cliff} for sand-sized and littoral-type sediment. Error ranges shown are those accumulated after taking the 1-σ range into account for each facies as shown in Table 1. Results show that the Q_{cliff} calculated using total sand-sized material is significantly different than that calculated for sediment coarser than the LCD, and the difference is as high as 124%. Results also show that the Merced Formation, with or without the LCD, is a significant source of sediment to the coastal zone.

Table 2. *Estimates of sand and littoral sand flux from rivers and sea cliff erosion to California littoral cells.*

Sediment Source	Littoral Cell	LCD (μm)	Sand Flux (m^3 yr^{-1})	Littoral Sand Flux (m^3 yr^{-1})	Percentage Overestimations
Merced Formation	SF	125	94,000 ± 5%	48,000 ± 17%	69–124
Little River	EK	125	40,500	27,200	49*
Mad River	EK	125	527,500	371,500	42
Eel River	EK	125	2,752,400	1,758,500	57
EK Cell Totals			*3,320,400*	*2,157,200*	*54*
Sea cliff erosion	SM	125	238,000	113,000	111
Sea cliff erosion	SP	105	6,000	1,500	300
Sea cliff erosion	LG	88	9,000	6,500	38
Sea cliff erosion	MB	105	96,000	59,000	63
Santa Maria River	SB	125	199,000	171,000	16
Ventura River	SB	125	76,000	58,000	31
Santa Clara River	SB	125	917,000	531,000	73
SB Cell Totals			*1,192,000*	*760,000*	*57*

SF = San Francisco, EK = Eureka, SM = Santa Monica, SP = San Pedro, LG = Laguna; MB = Mission Bay, SB = Santa Barbara.
* A detailed grain size analysis of sediment discharged from the Little River was not available; thus, the average littoral sand content from the Mad and Eel rivers was used to estimate the littoral sand flux for this river.

Discussion

Grain size analyses from beach samples show that a minimum grain size does exist in the study area and can be expressed in terms of an LCD, in which sediment finer than ~125 μm is not found in significant quantities. This grain size minimum allows a more site-specific evaluation of littoral inputs, such as sea cliff erosion, that can lead to better accuracy with regard to littoral sediment budgeting. In addition, using digital images of sediment along with the spatial autocorrelation algorithm of Rubin (2004) can be a useful and efficient tool for determining the LCD or for other coastal process studies.

Many facies in the Merced Formation consisting of paleo-beach deposits, such as the nearshore, foreshore, backbeach, and eolian facies, show little variation between the amount of sand-sized sediment and the amount of littoral-type sediment they contain (Table 1). However, the embayment and shelf facies show a significant difference, 38% and 68%, respectively, since they consist mainly of coarse silt and very fine sand. This is not a large difference insofar as the embayment facies are concerned, since they only make up 9% of the total formation as mapped by Clifton and Hunter (1987). The fine-grained shelf facies, on the other hand, dominate the Merced Formation, accounting for nearly 58% of the total stratigraphy and the majority of the outcrop area. Accordingly, the potential overestimation of 68% is significant, as reflected by the final estimations of Q_{cliff} presented in Table 2. The sand-sized Q_{cliff} is as much as 124% greater than its littoral-type counterpart, and estimates using the Wentworth scale as a sediment size restraint can significantly overestimate the actual amount of sand that is of sufficient size to contribute to a sediment budget.

Even though littoral drift rates along the coast near San Francisco may exceed 300,000 m^3 y^{-1} (Moffatt and Nichol Engineers, 1995), the 48,000 ± 17% m^3 y^{-1} of littoral sediment contributed by the Merced Formation represents possibly the largest point source of littoral-type sediment along the California coast between San Francisco and Santa Cruz (Figure 4). The only comparable source is the San Lorenzo River near Santa Cruz, which contributes an average of 25,000–30,000 m^3 y^{-1} of littoral-type sediment (Limber, 2005). The lack of large coastal-draining rivers along this stretch of coastline is an atypical pattern for California, since fluvially derived sediment usually comprises 75–99% of total littoral sediment (Best and Griggs, 1991; Runyan and Griggs, 2003), and suggests that sea cliff erosion may play a larger role in contributing sediment to the littoral system than previously thought.

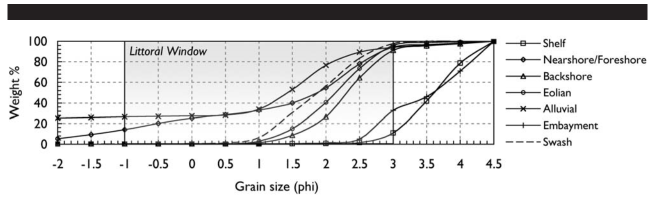

Figure 7. Average cumulative frequency grain size distributions for each facies within the Merced Formation. The "littoral window" denotes the sand fraction, based on a LCD of 125 μm (3 ϕ), of sand that is large enough to contribute to the littoral sediment budget.

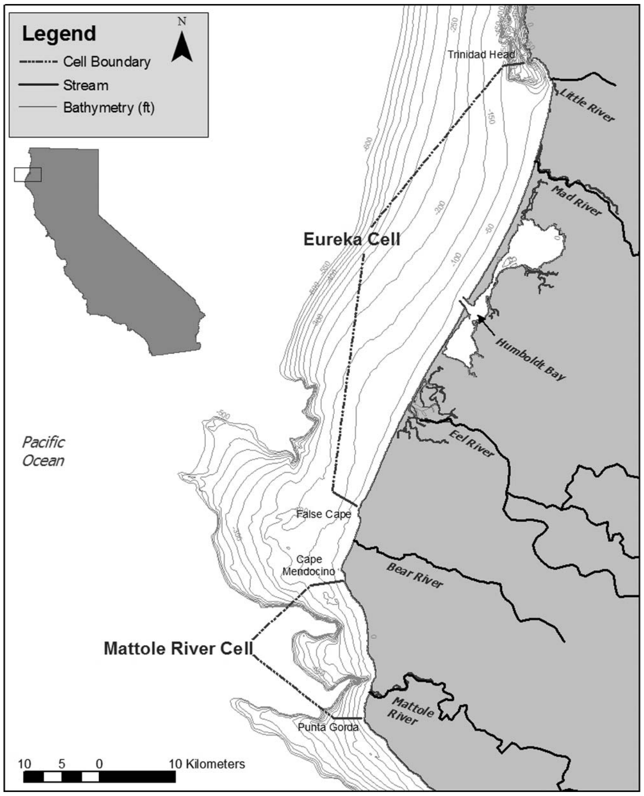

Figure 8. Location map for the Eel River and Mattole River littoral cells in northern California.

Figure 9. The mouth of the Eel River. The Eel River is a considerable source of sediment for the beaches of the Eureka littoral cell. Photo courtesy of Kenneth Adelman (www.californiacoastline.org).

CASE STUDY II: THE EUREKA LITTORAL CELL, CALIFORNIA

The Eureka littoral cell (Figure 8), located in Northern California, is approximately 67 km long and is bound by Trinidad Head, a prominent rocky headland, to the north, and False Cape to the south. The shoreline is comprised of beaches backed by large dunes from the Little River to the entrance of Humboldt Bay and narrow beaches between Humboldt Bay and False Cape. From False Cape southward, sandy beaches are nonexistent and the coast becomes very rocky. Beaches in the Eureka cell tend to be wide, flat, and composed of fine- to medium-grained sand (USACE, 1973). GLOGOCZOWSKI and WILDE (1971) found that the littoral cutoff diameter, or LCD (the diameter that less than 1% of the sand on the beaches is finer than), for beaches in this littoral cell to be 125 μm.

Ninety-nine percent of the sand entering the Eureka littoral cell is from the Little, Mad, and Eel rivers (PATSCH and GRIGGS, 2005). Sediment flux from these rivers, as well as from rivers mentioned in the following case studies, was estimated using a traditional rating curve technique (GLYSSON, 1987) based on discharge and sediment concentrations available from USGS gauging stations (USGS, 2006). It should be noted also that rating curve error could exceed 40% (BROWNLIE and TAYLOR, 1981).

The Little River, located ~6.5 km south of Trinidad Head and ~13 km north of the Mad River mouth, is the northernmost source of sediment for this cell. The present annual sand flux (sediment between 63 μm and 2000 μm) from the Little River is ~40,500 $m^3\ y^{-1}$. This is an overestimation of the sand input to the regional sand budget in this cell, however, because the finest sand grains that will remain on the beaches and will not be carried offshore (the littoral cutoff diameter) are 125 μm in size (GLOGOCZOWSKI and WILDE, 1971). Unfortunately, a more detailed grain size analysis of the sediment load that could allow for a more accurate calculation of the littoral sand supplied to the beaches by the Little River does not exist.

The Mad River is located ~18 km south of Trinidad Head and ~22 km north of the entrance to Humboldt Bay. The present annual sand flux (sediment coarser than 63 μm) from the Mad River is ~527,500 $m^3\ y^{-1}$ (WILLIS and GRIGGS, 2003; WILLIS, SHERMAN, and LOCKWOOD, 2002). With the LCD for this cell of 125 μm and sediment and water data compiled by WILLIS and GRIGGS (2003) from USGS gauging stations, however, the Mad River actually only contributes ~371,500 $m^3\ y^{-1}$ of sand annually that is coarse enough to remain on the beaches. Using the sand/silt break on the Wentworth scale causes an overestimation of ~156,000 $m^3\ y^{-1}$ of sand annually, or a 42% increase in the amount of beach-type sand entering the littoral system (Table 2).

On average, the Eel River (Figure 9) discharges more suspended sediment than any river in the lower 48 states after the Mississippi River (MEADE and PARKER, 1984), and the Eel River basin has one of the largest sediment yields per unit area in the world (BROWN and RITTER, 1971; HOLEMAN, 1968; JUDSON and RITTER, 1964). WILLIS and GRIGGS (2003) compiled all current USGS water and sediment data for the Eel River through the 2000 water year at the USGS gauging station at Scotia located ~35 km from the coast. According to these data, the annual sand discharge (between 63 and 2000 μm) averaged over 89 years (from 1911 to 2000) is 2,752,400 $m^3\ y^{-1}$ (Table 2). However, the yearly sand discharge ranges from nearly 27,000,000 m^3 in 1965 to 3200 m^3

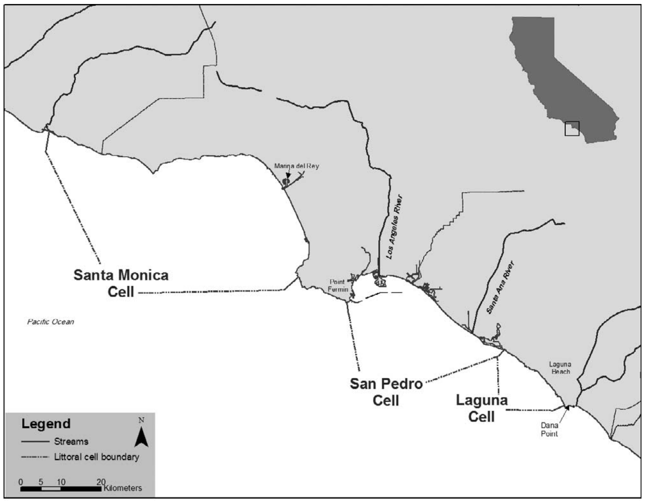

Figure 10. Location map for the Santa Monica, San Pedro, and Laguna littoral cells in southern California.

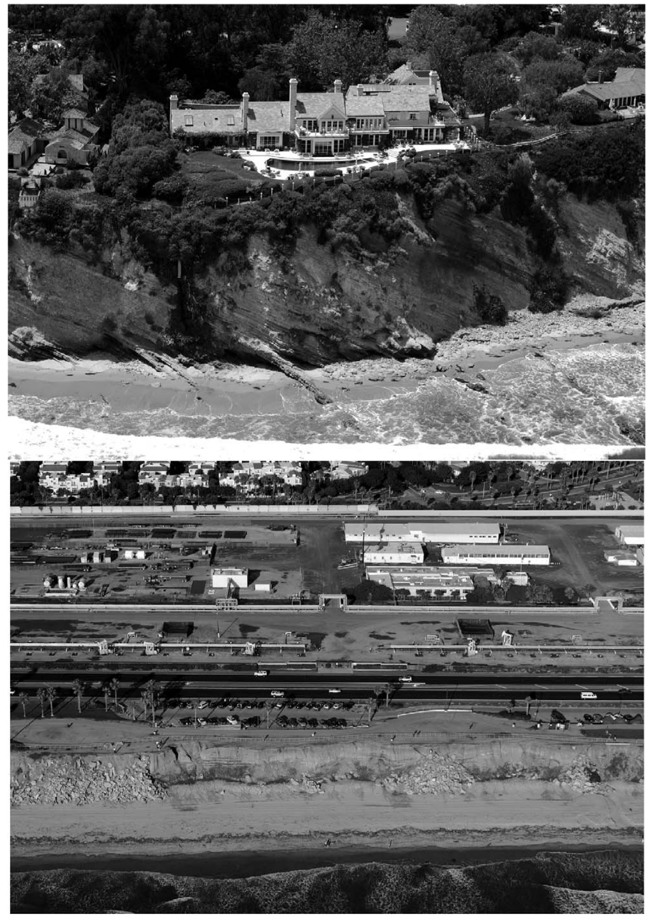

Figure 11. Eroding sea cliffs in the Santa Monica littoral cell near Malibu (top), and Pleistocene sea cliffs in the San Pedro littoral cell at Huntington Beach. Photos courtesy of Kenneth Adelman (www.californiacoastline.org).

in 1977. Sand-sized material, according to the Wentworth scale (between 63 and 2000 μm), constitutes ~25% of the sediment yield with bed load assumed to be ~4% of the total load (HAWLEY and JONES, 1969; WILLIS and GRIGGS, 2003). In addition, sand from the Van Duzen River, a tributary to the Eel River, adds an estimated 137,000 $m^3\ y^{-1}$ (BROWN and RITTER, 1971; WILLIS, SHERMAN, and LOCKWOOD, 2002).

When using the LCD, the Eel River is found to contribute an average of only ~1,758,500 $m^3\ y^{-1}$ of beach-type sand annually. If the LCD is not used to determine the sand supplied to the beaches by the Eel River and the Wentworth sand/silt break of 63 μm is used, the volume of sand entering the littoral system is overestimated by nearly 1,000,000 $m^3\ y^{-1}$ (Table 2), which is enough to create a beach 3.3 km long, 3 m deep, and almost 100 m wide.

In total, using the Wentworth sand/silt threshold of 63 μm instead of the LCD for rivers entering the Eureka littoral cell in California could result in a total overestimation of sand entering the littoral system on the order of nearly 1.2 million $m^3\ y^{-1}$. Overestimations of this magnitude may have serious implications to coastal planning and engineering practices along this stretch of shoreline.

CASE STUDY III: SEA CLIFFS IN SANTA MONICA, SAN PEDRO, LAGUNA, AND MISSION BAY LITTORAL CELLS, CALIFORNIA

Littoral sediment flux from sea cliffs in the Santa Monica, San Pedro, Laguna, and Mission Bay littoral cells (Figures 10, 11, and 12; Table 2) was determined by PATSCH and GRIGGS (2005). Sea cliffs range from 3 to 100 m in height and back approximately 75 of the 188 km of total shoreline in these cells. With a similar method to that described above for the Merced Formation, annual sediment flux was quantified using the Wentworth sand/silt break of 63 μm as well as the LCD to determine the percentage difference between the two methods. The LCD found for each cell ranges from 88 to 125 μm (Table 2). Using the Wentworth scale results in an overestimation of sand entering the littoral system of 111% (125,000 $m^3\ y^{-1}$) in the Santa Monica cell, 300% (4500 $m^3\ y^{-1}$) in the San Pedro cell, 38% (2500 $m^3\ y^{-1}$) in the Laguna cell, and 63% (37,000 $m^3\ y^{-1}$) in the Mission Bay cell (Table 2). These overestimations are due to the fact that many of the sea cliffs are composed primarily of fine sand that may be too small to contribute to the sediment budget. Overall, failure to use the LCD when estimating the sand contribution from sea cliff erosion to the littoral cell sand budgets mentioned above will result in a total overestimation of sand of approximately 169,000 $m^3\ y^{-1}$ or 94%.

CASE STUDY IV: THE SANTA CLARA, VENTURA, AND SANTA MARIA RIVERS IN THE SANTA BARBARA LITTORAL CELL, CALIFORNIA

The Santa Barbara littoral cell is arguably the longest littoral cell in southern California, extending 230 km from the mouth of the Santa Maria River, around Point Conception, and terminating at Point Mugu into the Mugu Submarine Canyon (PATSCH, 2004; the importance of Point Conception

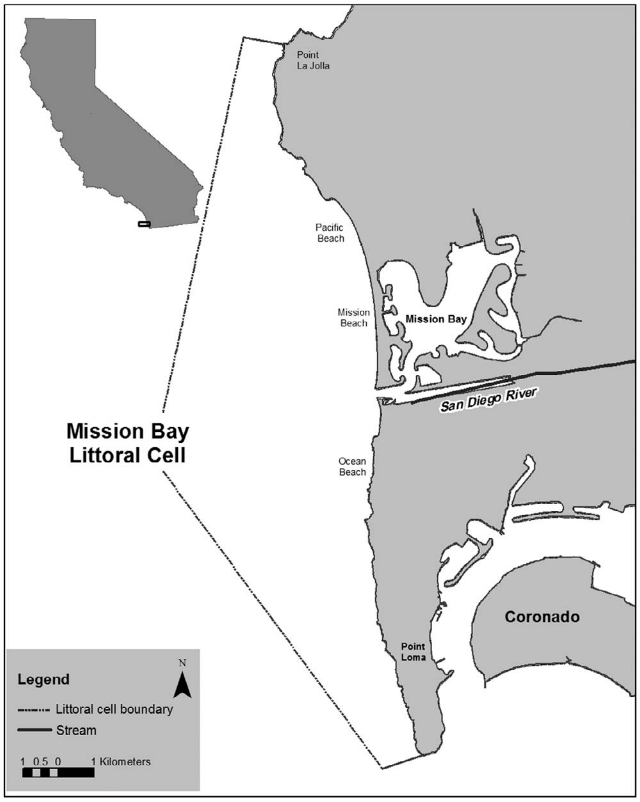

Figure 12. Location map for the Mission Bay littoral cell in southern California.

as a partial littoral barrier has been a subject of disagreement for decades). The Santa Barbara littoral cell has four main contributing rivers (Santa Maria, Santa Ynez, Ventura, and Santa Clara) and a number of smaller streams (San Antonio Creek, Santa Ynez mountain streams, and Calleguas Creek) that, together, currently contribute 99.5% of the sand (coarser than 63 μm) to this littoral cell (Runyan and Griggs, 2002; Willis, Sherman, and Lockwood, 2002). Three of these rivers, the Santa Clara, Ventura, and Santa Maria, have extensive water and sediment data compiled by Willis (personal communication, 2003) through the 2000 water year at USGS gauging stations, which allows for a comparison of sand supplied to the beaches in this littoral cell when using the Wentworth sand/silt break of 63 μm and the LCD for this cell of 125 μm.

After a detailed analysis of the water and sediment data for these three rivers, it was determined that using the Wentworth sand/silt break of 63 μm will cause overestimations of sand entering the littoral cell on the order of 16%, 31%, and 73% for the Santa Maria, Ventura, and Santa Clara rivers, respectively, and totaling 432,000 m^3 y^{-1} (Table 2).

CONCLUSIONS

As demonstrated by the preceding case studies, the LCD is a working concept that can be a valuable tool in quantifying active sediment inputs within a sediment budget framework. By relying effectively on the size of sediment already present in a given littoral cell that has been shaped by ongoing hydraulic and geomorphic processes instead of the Wentworth scale, a more accurate estimation of the amount of beach-building sediment contributed from individual, as well as regional, sediment sources can be made. Results show that, in a variety of California coastal settings, the size of sand on a beach does not necessarily correlate with the definition of sand provided by the Wentworth grain size scale. It follows that reliance on the grain size scale to characterize littoral sediment inputs can lead to significant overestimations, since the range of sand grain sizes on a beach is typically much narrower than that defined as sand by the Wentworth scale. These overestimations of contributing littoral sand are more pronounced in sediment sources that contain large fractions of fine sand, such as the Eel River, the Merced Formation, and the eroding sea cliffs of the San Pedro and Santa Monica littoral cells. In these cases, possible overestimation ranges from 57% to a maximum of 300%, and the large discrepancy has significant implications for quantifying sand inputs to California's beaches. Although this study focuses wholly on applications of the LCD to the coast of California, the LCD concept is one that can be relatively easily applied on other coastlines to more precisely quantify active sediment inputs and gain a better understanding of the individual sediment sources that supply littoral sand to the coastline.

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