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Are
"Stable Shorelines"
and
"Broad Beaches"
Mutually Exclusive Management Goals
Along Southern Monterey Bay?

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Preface

Coastal erosion threatens both public and private lands in Monterey County. On January 18, 2005, a panel convened to investigate strategies for managing coastal erosion along southern Monterey Bay. The members of the panel and subsequent working group include representatives from USGS, California Coastal Commission, Monterey County, CSU Monterey Bay, City of Monterey, City of Seaside, NOAA, private consulting firms, Naval Postgraduate School, UC Santa Cruz, and the Monterey Bay National Marine Sanctuary.

This report summarizes the relevant work of Dr. Douglas Smith and students at CSU Monterey Bay. The report details some of the key coastal geomorphic concepts presented to the coastal erosion panel by Ed Thornton on January 18, 2005 and Douglas Smith on March 21, 2005. This brief report does not cite all the original studies that contribute to our understanding of the regional coastline. The reader needing further original references are directed to the recent publications of Dr. Ed Thornton and Dr. Gary Griggs (UC Santa Cruz).

This report may be cited as:

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It may be accessed on the internet on the Central Coast Watershed Studies publications page: <http://science.csumb.edu/%7Eccows/> .

Acknowledgements

Dr. Ed Thornton and colleagues at the Monterey Naval Postgraduate School have developed the most complete accounting of the sand budget in the southern Monterey Bay region. Dr. Thornton presented his unpublished data to the coastal erosion panel on January 18, 2005. His forthcoming papers will be the best reference to date of the sand budget and nearshore processes in southern Monterey Bay. With Dr. Thornton's permission we report here some of the preliminary estimates of sand transport from his work.

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1 Executive Summary

The coastline of southern Monterey Bay has moved many kilometers east and west in response to oscillating sea level changes and vertical tectonics active over the last 2 million years. The most recent episode of coastal retreat began about 18,000 years ago as the most recent ice age began to wane, replenishing the Earth's sea water volume through ice cap melting. An internet-based animation introduced with this report (Hofmann, 2004) illustrates the inexorable eastward progress of the coastline during the most recent sea level advance. Long term average retreat rates of somewhat less than 1 m/yr can be estimated from bathymetric charts and the fact that sea level was located approximately 130 m lower 18,000 years ago than it is today. More detailed surveys of coastline position in aerial photographs from the past few decades, and more recently obtained LIDAR data and GPS records indicate modern retreat rates average approximately 1 m/yr, but are variable along the coast. The seaward end of the north jetty of Moss Landing Harbor projects into the Monterey Canyon head, so virtually all the sand moving south from Santa Cruz is guided into the canyon head, leaving little to add to the southern Monterey Bay sand supply.

A systematic sand-budget approach to analyzing the coastal morphology suggests that sea cliff erosion may provide a very significant input of sand to the nearshore region. If that conclusion is true, then the broad beaches that typify most of southern Monterey Bay in large part owe their existence to coastal retreat, and would be compromised by coastal armoring. This apparent paradox is important for coastal management decisions. Armoring the coastline to reduce sea cliff erosion would clearly remove an important source of beach sand, probably leading to narrower or absent beaches. Reducing the loss of beach sand to offshore storage through wave energy dissipation offers an alternative approach. However, offshore structures designed to reduce wave energy would be technically challenging, and would alter the Monterey Bay Sanctuary ecosystem in both predictable and unforeseen ways. Structures may have unforeseen physical results as well. It is clear that a knowledge of geomorphic principals and local erosion rates are critical components in the decision matrix for treating coastal erosion in southern Monterey Bay. Cost-benefit analysis for engineering solutions to coastal retreat should have contingencies for eventual failure and decommissioning at the end of the predicted life of the project in the estimated cost.

2 Introduction

Coastal erosion is a global problem that is felt in every coastal state of the U.S (Fig. 1). The most obvious negative result of coastal erosion is the loss of valuable public and private land area. The chief environmental variables that generally contribute to high coastal erosion rates include sporadic high surf, global sea level rise, coastal subsidence, sediment trapping behind dams, floodplain storage along low-gradient coastal valleys, and human endeavors such as sand mining and structural modifications of the coastline (e.g., Morton, 2003; DBWSCC, 2002).

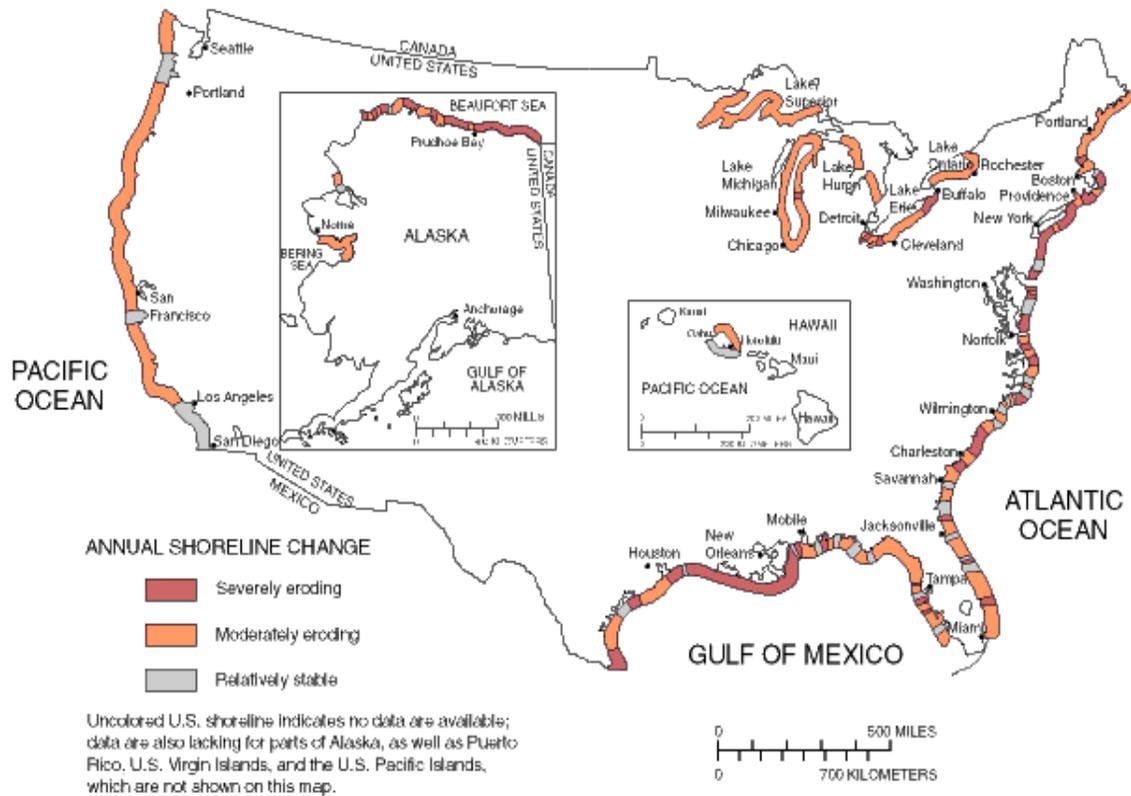


Figure 1: Coastal erosion hazards along the U.S. coastline (USGS, 1985).

Monterey Bay (Fig. 2) was classified by the USGS (1985) as relatively stable (Fig. 1). The existence of broad beaches (Fig. 3) along the reach of coastline between Moss Landing and the Municipal Wharf in Monterey has been incorrectly interpreted to mean that the coastline is fixed in space, and not subject to coastal retreat.

It is our hope that an accurate understanding of the data and physical processes of the southern Monterey Bay coastline will be used to create sound coastal management policy. In this report, we introduce the following data and concepts with the goal of developing a shared understanding of the how the southern Monterey Bay coastline system works.

- Geological and geomorphic setting, focusing on sea cliff materials
- Long term erosion estimates based upon sea level rise
- Methods employed to determine coastal retreat rates
- Results of recent studies placed into a geomorphic and sand budget framework
- Systematic sand budget approach to making management decisions

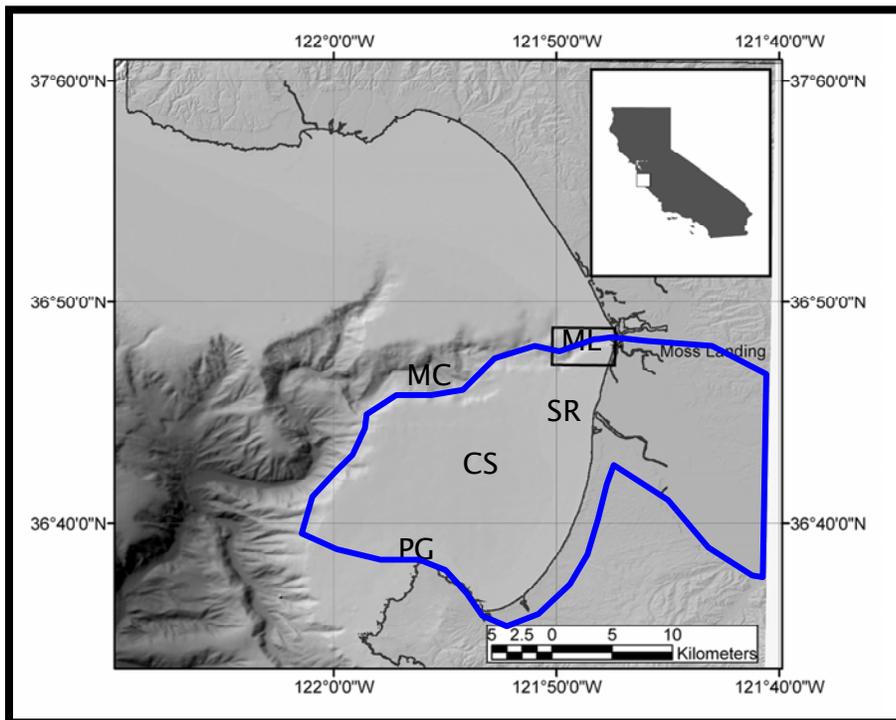


Figure 2: Southern Monterey Bay extends from Moss Landing (ML) to Pacific Grove (PG). The system is bounded on the north and west by Monterey Canyon (MC). The beaches rim a broad continental shelf (CS). The outline generally defines the region discussed in this report. The Salinas River (SR) delta forms a bulge in the coastline south of Moss Landing.



Figure 3: Broad sandy beach located in Monterey.

3 Geologic and Geomorphic Setting

The coastline of southern Monterey Bay comprises a broad, sand and mud draped continental shelf (Fig. 2). The eastern edge of that continuous sediment carpet is the intermittently-dry sand called the beach (Fig. 4). Along southern Monterey Bay, the eastern border of the beach is typically either an easily eroded sea cliff face (Fig 5) or active dunes (Fig. 6). In a few places, the beach is bounded by a sea wall or other structure meant to reduce erosion rates (Fig. 7).

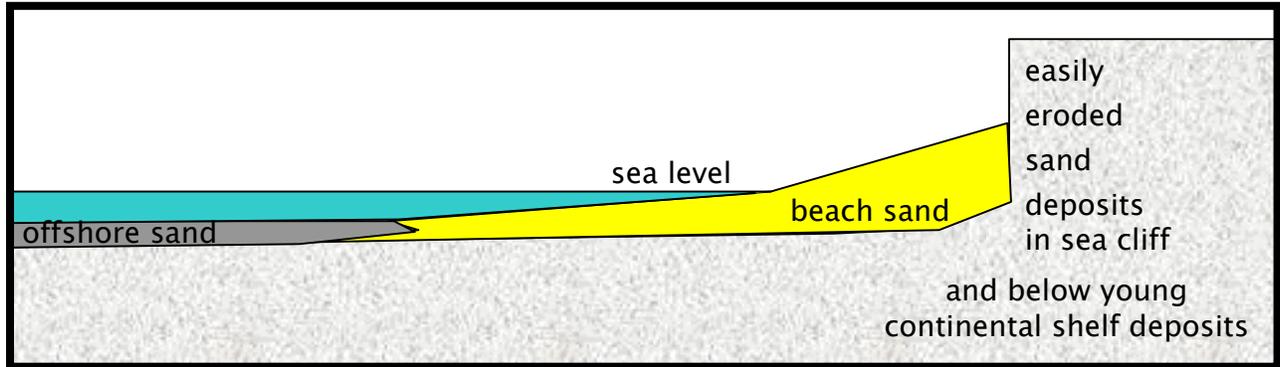


Figure 4: Schematic cross section showing thin sand veneer atop older sand deposits that compose the sea cliff. This diagram is typical of the sea cliff from Marina to Sand City, and south of the Monterey Beach Resort until a kilometer northeast of the Monterey Municipal Wharf.



Figure 5: Sea cliffs along Marina composed of old, eroding dune deposits (October 31, 2004).



Figure 6: Vegetated modern dunes behind near Monterey Beach Resort (Gref, 2005)



Figure 7: Sea wall protecting Ocean Harbor House Condominiums. December 9, 2004.

The material comprising the eroding sea cliffs is older sand dune deposits from a now relict system of dunes. Some of the sea cliff derived sand is blown back inland to feed modern dunes that are sporadically present. As discussed later, most of the sand eroded from the cliffs is thought to drift offshore after a short residence time in the sand beach (Thornton, 2005).

4 Sea Level Rise and Long Term Coastal Retreat Rates

There have been long periods in Earth's history when there were mild, well-buffered temperatures over much of the planet. Occasionally the mild climate is punctuated by a series of ice ages. The most recent series of ice ages began 2 million years ago, marking the beginning of the Quaternary Geologic Period.

During the Quaternary Period there have been as many as 20 distinct ice ages, where temperatures have plummeted, polar ice caps have formed, and sea levels have dropped as water was frozen into the caps. During each ice age, shorelines and all their associated physical processes and ecosystems migrated offshore. With each warm period between ice ages, ocean basins refilled (Fig. 8) and the shorelines migrated back up onto the continents.

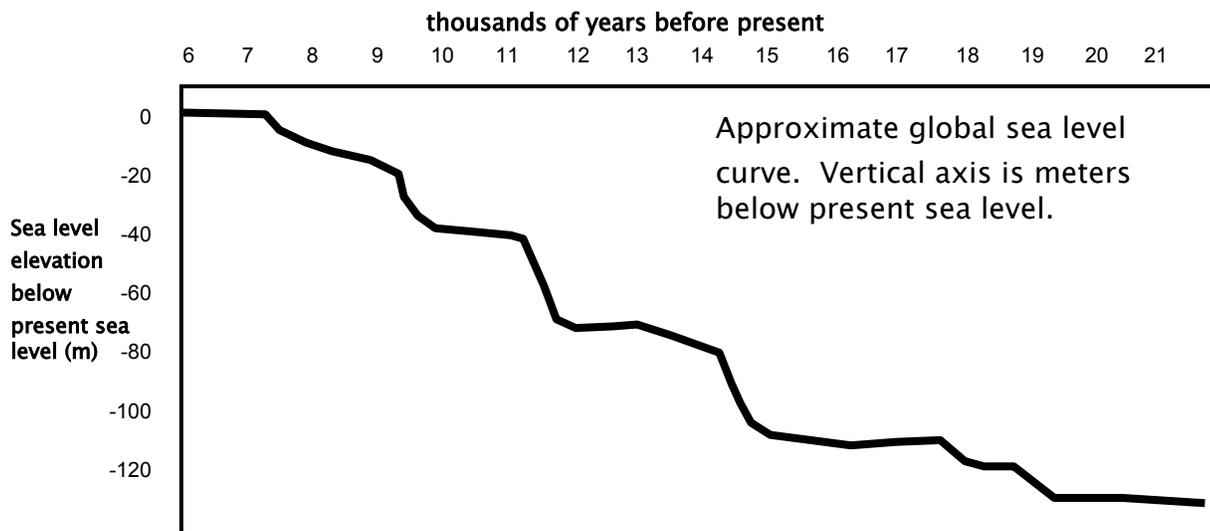


Figure 8: Sea level rise over the past 18,000 years. This curve is compilation of data from Tahiti, Barbados, and Caribbean sites, from data compiled by Dr. Thomas Rockwell, San Diego State University.

The acme of the most recent ice age was about 18,000 years ago. At that time sea level was approximately 130 m (425 ft) lower than present sea level along central California (e.g. Pinter and Gardner, 1989), and the beach was located along the rim of Monterey Canyon (Figs. 9 and 10).



Figure 9: Digital elevation model of low sea level (blue) in Monterey Canyon head. View extends from Moss Landing Harbor (ML) out to sea 4 km, to a depth of 270 m. The rectangular box around “ML” in Figure 2 shows the position of this view. Bathymetric data from the CSUMB Seafloor Mapping Lab (<http://seafloor.csUMB.edu/index>).

Figure 10 shows southern Monterey Bay 18,000 years ago. During the low stand of sea level (Fig. 10), the exposed continental shelf (gray color) was partly (or completely) covered by sand dunes in a dune field that spanned the Salinas Valley and migrated inland to parts of Fort Ord lands where relict dunes are still preserved. In fact, the last 2 million years have left several layers of dune deposits in the region, including the Aromas Sandstone. These dune deposits are the weak substrate exposed in sea cliffs that the present sea level is eroding in southern Monterey Bay. We can speculate that the dune field may have been locally vegetated adjacent to the extensions of the Salinas River, Canon Del Rey Creek, Iris Creek, and other smaller drainages on the Monterey Peninsula that coursed through that ancient coastal plain. Respectively, Figures 11 and 12 show sea level at today’s location and a predicted position in the year 2200, 200 years from now. In the future (Fig. 12), the Salinas coastal lagoon will expand into a broad estuary like historic Elkhorn Slough.

ML=Moss Landing
MC=Monterey Canyon
SV=Salinas Valley
SS=Seaside
PG=Pacific Grove
CV=Carmel Valley

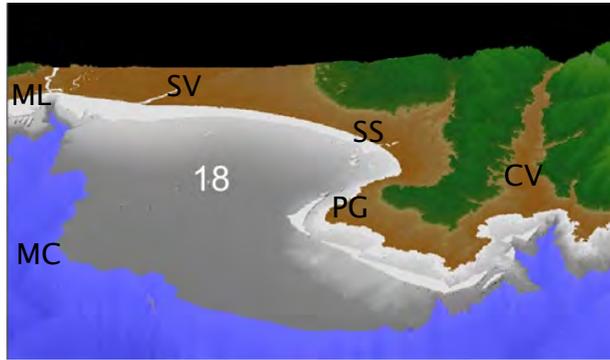


Figure 10: Shoreline position at approximately 18,000 years ago, at the acme of the most recent ice age (Hofmann, 2004).

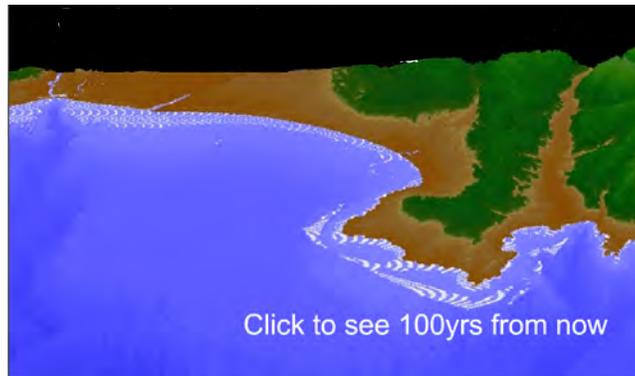


Figure 11: Shoreline position in 2005 (Hofmann, 2004).



Figure 12: Shoreline position in 2200 (Hofmann, 2004).

The animation of sea level rise (Hofmann, 2004) simplifies the sea level curve by assuming a constant rate of rise. The rate has been variable, and has been very slow for the past 5000 years (Fig. 8). Despite the recent slow rate of sea level rise, shorelines have continued to rapidly retreat (Fig 1) as wave energy inexorably wears away shoreline rock and sand.

The coastal retreat rate is the velocity at which the shoreline is moving inland, converting dry land into marine continental shelf. The retreat rates are estimates based upon the distance of shoreline retreat divided by the length of time over which occurs. The rate of coastal retreat averaged over the 18,000 years since the most recent sea level low stand is the distance from the modern shore to the 130 m depth contour on the continental shelf (ancient shoreline position) divided by 18,000 years. The rate derived for southern Monterey Bay at approximately Seaside is approximately 14,000 m divided by 18,000 years or 0.8 m/yr (2.6 ft/yr).

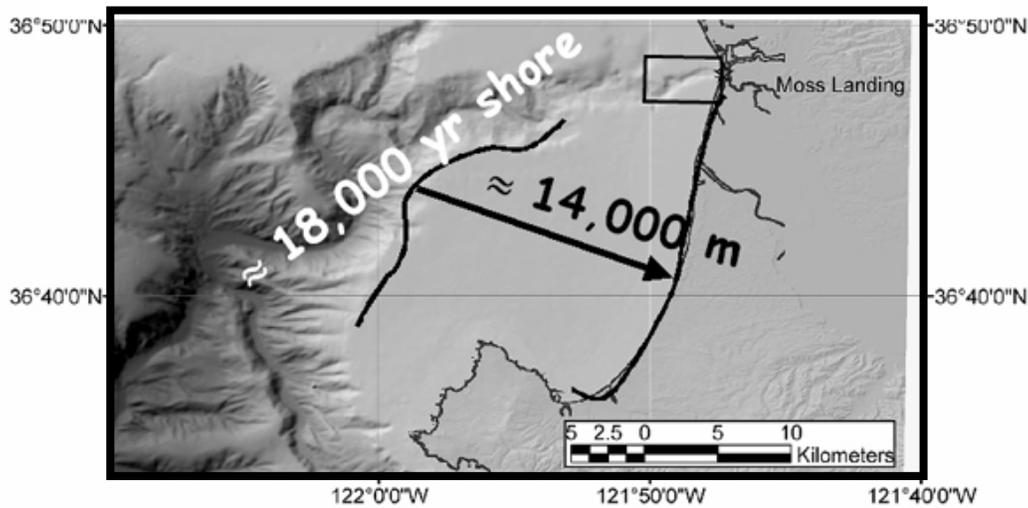


Figure 13: Figure for calculating 18,000 year coastal retreat rate. Black line offshore represents shoreline 18,000 years ago when sea level was approximately 130 m below present sea level. See more accurate bathymetric chart in Appendix A.

5 Recent Surveys of Coastal Retreat

Coastal retreat can be monitored in a variety of ways. Each method has its unique spatial coverage, precision, accuracy, and cost. Recently employed monitoring and survey methods have increased our understanding of coastal retreat in southern Monterey Bay including direct observation, oblique photos from the ground and air, analysis of historic and recent aerial photographs, GPS surveys, and serial aerial LIDAR surveys. Future high-resolution surveys will likely include oblique terrestrial LIDAR surveys. Below we present some examples of each kind of data, and some recent results from Gref (2005).

5.1 Oblique Photos

Snapshot photographs from the ground or air can provide a valuable record of instantaneous geometry (Fig 14). Such photographs convey information about landscape condition and recent processes and can be part of a series of similar shots that record geomorphic change through time (e.g., Figure B1 and B2). USGS (1999) provides a catalog of oblique aerial photography documenting coastal change associated with the 1998–99 El Nino season. Smith (2005) includes an annotated documentation of seasonal changes at the Monterey Beach Resort and other local sites.

Figure 14 shows a typical southern Monterey Bay sea cliff composed of relict sand dune deposits with very low resistance to erosion. The brown streak in the cliff is an exhumed ancient soil horizon within the dune deposits. The base of the cliff is an apron of loose sand sloughed from the constant incremental retreat of the seacliff. The basal sand apron is perennially present, and is intermittently refreshed by sloughing from above, and intermittently depleted as the sand is transferred to the beach by wind, gravity, and tides.

There are several other examples of oblique photography in this report text and in Appendix B.



Figure 14: Oblique aerial photograph of Seaside sea cliff taken on October 31, 2004.

5.2 Historic aerial photos and GPS

The most accurate method for estimating coastal retreat is to identify a conspicuous feature of the beach system, and track its position through time by comparing dated, well-matched, and georeferenced aerial photographs and digital aerial photographs. Features that are easy to see in photographs include the cliff edge, or intersection of dunes and back beach.

Retreat rates of the coast have been estimated in this way by several independent workers. In each case the results are similar, lending credence to the high retreat rates they found. The Department of Navigation and Ocean Development reports an average shoreline retreat rate of about 1.5 m/yr rate between 1946 and 1967. Arnal et al (1973) reports an increase in shoreline erosion rates in Fort Ord from 0.5–0.6 m/yr in the 1920's, to about 0.9 m/yr in the 1950's, increasing to 1.5 m/yr in the 1960's. Historically, the highest average dune/bluff retreat rate occurs in the Fort Ord area, "...approximately up to 2.4 m/yr at Stillwell Hall, due to wave refraction patterns over Monterey Submarine Canyon that produce large waves in this area" (Griggs and Savoy, 1985). Farther south the retreat rate decreases to an average of 1.8 to 1.5 m/yr in the Marina area and diminishes to an average of 0.9 to 1.5 m/yr in the Sand City area (Griggs & Savoy, 1985).

More recently Gref (2004) estimated coastal retreat rates at four sites between Marina State beach and Del Monte State beach. The four sites are Marina State Beach, Stilwell Hall, Monterey Beach Resort, and Ocean Harbor House Condominiums (Fig. 15). These areas were selected because there are landforms for easy georeferencing, the locations were representative of several locations along the Bay, and most of the areas had buildings on or near the coast that may be impacted by further coastal retreat. Gref (2004) used historic aerial photography, high resolution digital aerial photographs from 2002, and GPS technology to map the most recent geometry.

At each site several transects were measured orthogonal to the beach on each pair of photographs (Fig. 16), and the average retreat rates were determined for four time steps representing the past 28 years. The data are summarized in Figure 17 and Table 1.

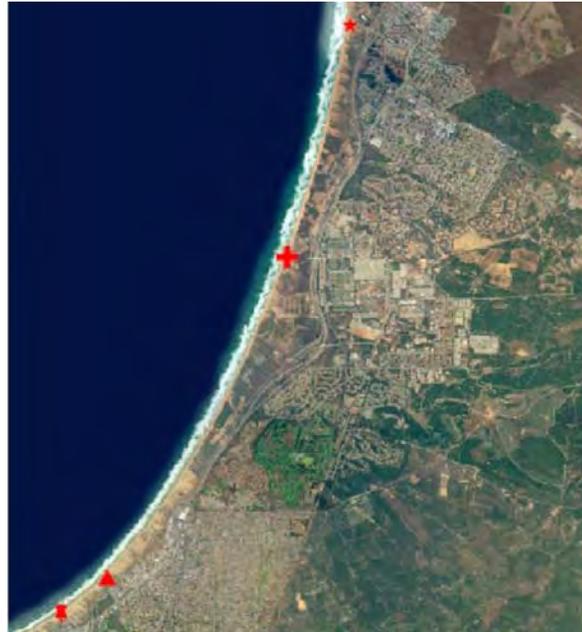


Figure15: Four sites studied by Gref (2004). From top to bottom Marina State Beach, Stillwell Hall, Monterey Beach Resort, and Ocean Harbor House Condominiums. See Figure B2 for Stillwell Hall, Figure B5 for Monterey Beach Resort, and Figures B3 and B4 for Ocean Harbor House Condominiums.

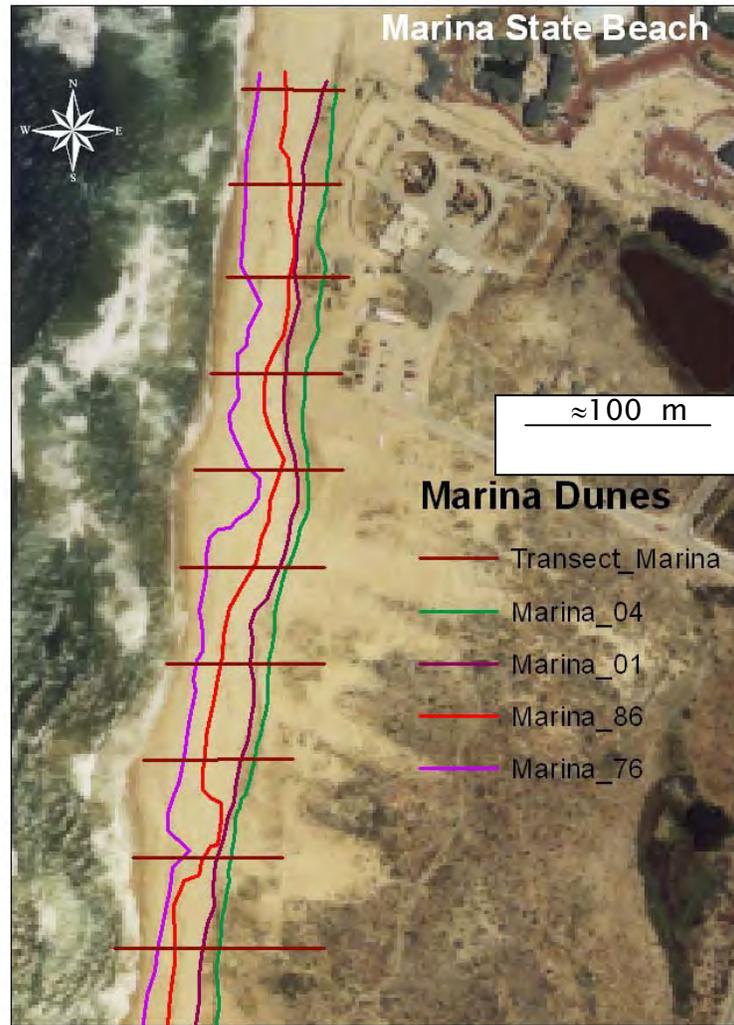


Figure16: Method of determining retreat rate at Marina Dunes study site. Long lines are dune-beach intersections of 2004, 2001, 1986 and 1976 plotted on the 2001 digital aerial photograph. The short lines are ten transects across the images used to determine average retreat rates at the site. Each of the four study sites (Marina, Stillwell, Resort, Condominiums) were similarly assessed.

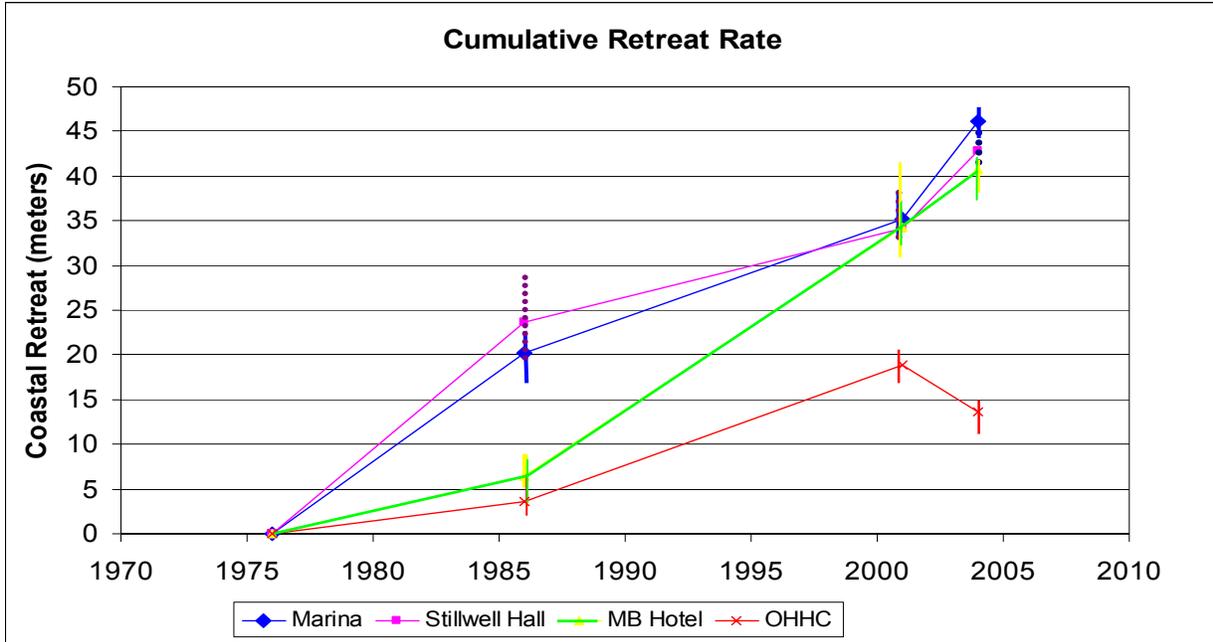


Figure 17: Cumulative coastal retreat over 28 years for each site. Error bars use the 95% confidence level found in Table 1.

Table 1: Coastal retreat rates at four study sites in southern Monterey Bay

Marina State Beach Based Upon 10 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	20.2	7.0	5	2.0	20.2
1986-2001	15	15	7.1	5	1.0	35.2
2001-2004	3	10.9	3.9	3	3.6	46.1
Stillwell Hall Based Upon 14 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	23.6	16.4	9	2.4	23.6
1986-2001	15	10.5	10.7	6	0.7	34.1
2001-2004	3	8.7	5.7	3	2.9	42.9
Monterey Beach Resort Based Upon 14 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	6.4	5.8	3	0.6	6.4
1986-2001	15	27.8	21.4	12	1.9	34.2
2001-2004	3	6.6	4.6	3	2.2	40.8
Ocean Harbor House Condominiums Based Upon 6 Transects						
Data Years	Time (yrs)	Coastal retreat (m)*	Standard Deviation (m)	95% Confidence Interval (m)	Retreat Rate (m/yr)	Cumulative Retreat (m)
1976	0	0	0	0	0	0
1976-1986	10	3.7	4.6	5	0.4	3.7
1986-2001	15	15.2	5.1	5	1.0	18.8
2001-2004	3	-5.3	5.0	5	-1.8	13.6

5.3 Aerial LIDAR

Aerial “Light Distance And Ranging” (LIDAR) technology produces accurate and precise three-dimensional coordinates of points at the surface of the Earth along the flight path of the aircraft carrying the instrument. Figure 18 is an example of a shaded relief image produced from digital LIDAR data. LIDAR data has been collected along southern Monterey Bay on several occasions, most recently in 2004. Since the data sets are digital, the individual pixels in the images can be compared from year to year to detect changes. Dr. Ed Thornton (Naval Postgraduate School, Monterey) is currently publishing a series of papers that use LIDAR data to estimate both the lateral erosion rates and sand volume loss along much of southern Monterey Bay.

We found that the 2004 LIDAR data are very accurate and precise using an electronic total station and RTK GPS receiver to independently survey features that are visible in the LIDAR data set in the Elkhorn Slough, inland of Moss Landing (Appendix C). The study indicates that the elevation of every 1m² pixel in the LIDAR data set is known with an error of less than 10 cm. Horizontal positions were reasonably accurate as well.

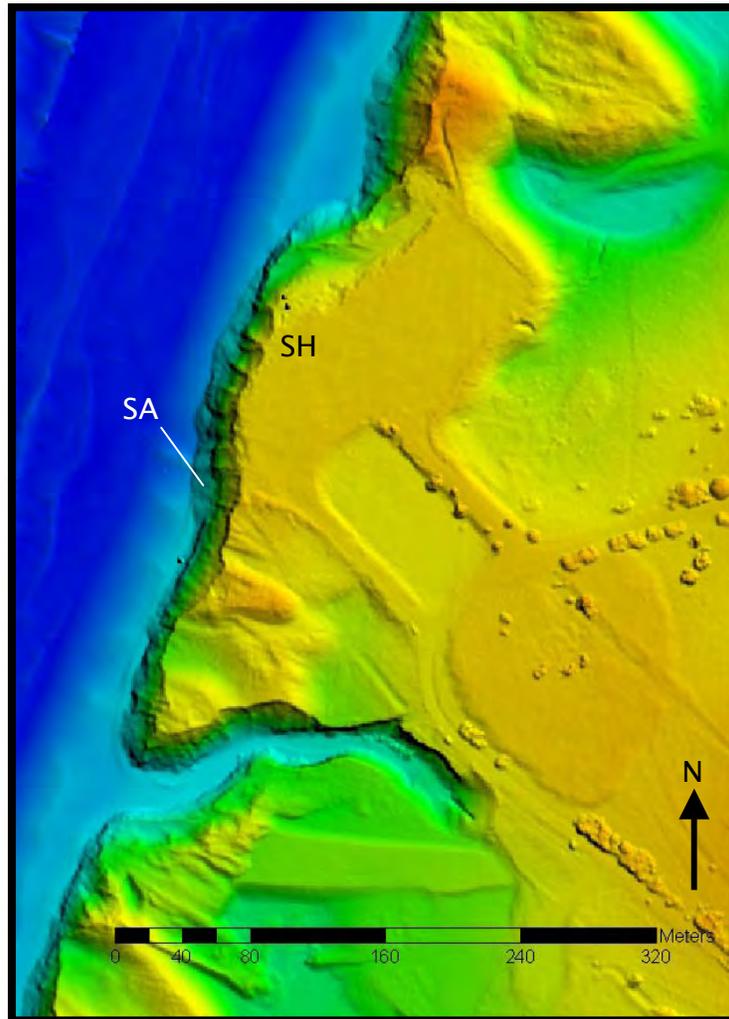


Figure 18: Shaded relief image from 2004 LIDAR data shows former Stillwell Hall site (SH). Sand aprons are visible at the base of steep sea cliffs (e.g., SA). Canyon (near the scale bar) rapidly eroded in response to broken storm drain. The storm drain had been undercut by coastal retreat. See Figures B8 and B9 for oblique ground photographs of the mouth and apex of the canyon. Data courtesy of Dave Lott (Monterey NOAA).

5.4 Terrestrial LIDAR

Terrestrial LIDAR systems are used on a tripod rather than in an aircraft. The instrument is aimed at the landscape to be digitized, and the LIDAR system acquires the three dimensional coordinates of millions of individual points in the view. This technology could be rapidly used to determine local coastal retreat rates with a precision of 4 mm. To our knowledge no such data sets exist yet for southern Monterey Bay.

6 Sand Budget and Beach Equilibrium

Our beaches are fed sand from a few sources and, in turn, lose sand to the continental shelf. If there is a balance between sand entering and leaving the beach, then the beach maintains its shape. If there is an imbalance in sand moving in and out of the beach, then it either grows or shrinks, depending upon which process prevails. Interestingly, the beach can maintain its average size even in the context of coastal retreat (Fig 19). Average beach size will remain constant when the sand provided by sea cliff retreat balances the sand lost to the continental shelf (Fig. 20), whether the coastline is stationary or migrating through space. The amount of sand provided to the beach by the process of seacliff retreat along southern Monterey Bay has recently been estimated to be 270,000 m³/yr (Thornton, 2005).

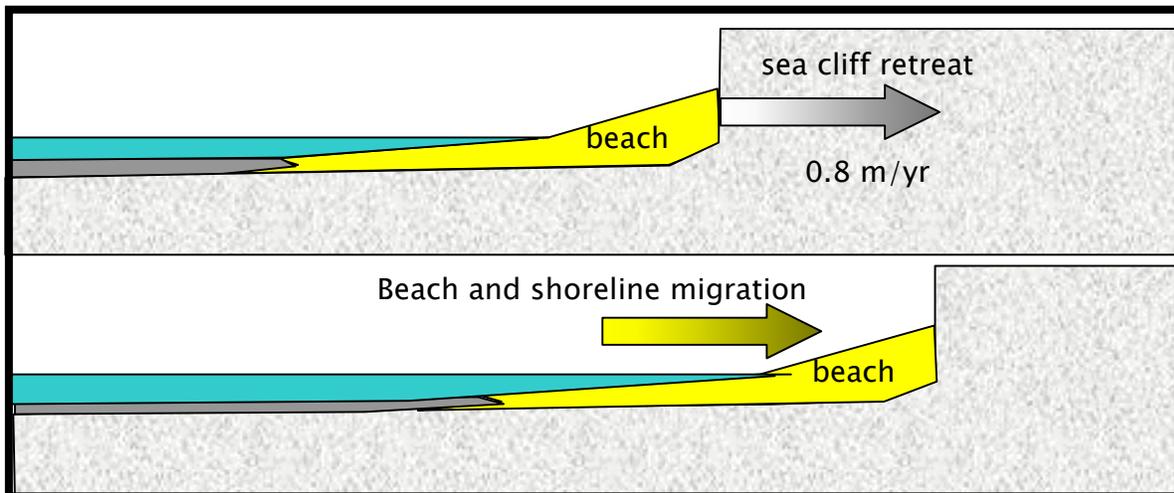


Figure 19: As coastal retreat progresses, the whole system moves eastward as an intact triad of offshore sand, beach, and seacliff. The beach geometry in the bottom figure is the same as in the top figure, except that the system has migrated eastward. In this example, the beach size has not changed because net sand input balances net sand output.

A useful tool for understanding beach processes is to create a sand budget for the beach. In the budget the inputs and outputs are measured as closely as possible, and the balance between the two is the change in storage of sand on the beach (Figures 21 and 22). The analytical process is the same as managing a checkbook and bank account, where the volume of beach sand at any point in time represents the amount of money in the bank. Creating a sand budget can also allow predictions to be made about the likely result of various coastal management options.

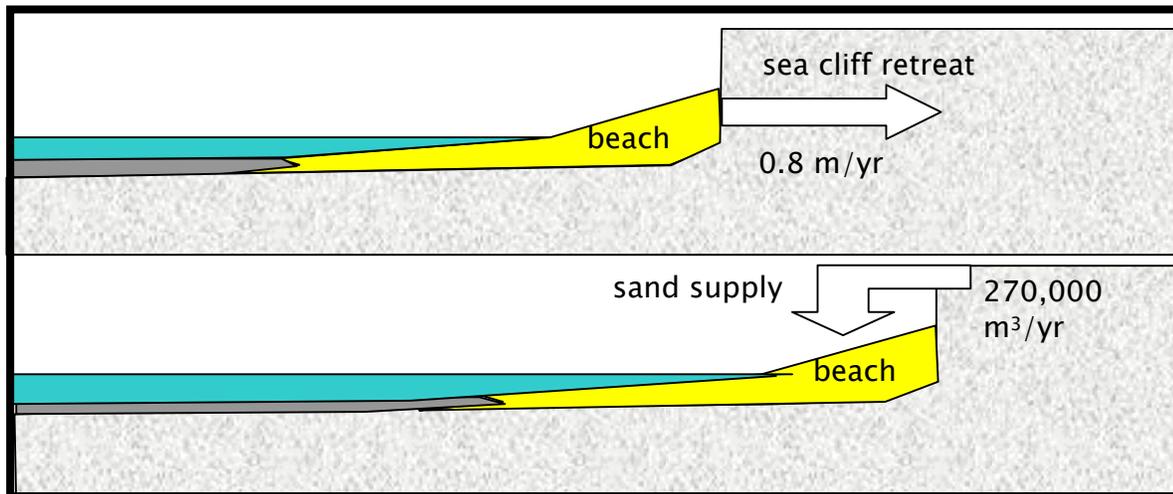


Figure 20: As coastal retreat progresses, the cliff erosion supplies the beach.

Figure 22 represents a conceptual framework of the physical processes that add, transport, store, or remove sand from any specific reach of the beach. It is analogous to knowing where your dollar earnings come from and where they go, but without assigning dollar values to the transactions. A more useful model would have at least some of the volumes of sand storage and some input and output rates. Sediment transport rates are, by nature, very difficult to assess. The transport estimates are complicated by the strongly episodic nature of the process. For example, much of our decadal erosion occurs during the few strong storms generated by El Niño events (Thornton, 2005; DBWSCC, 2002, Storlazzi and Griggs, 1998; Dingle and Reis, 2002). Thornton (2005) presented unpublished results that represent the best estimates of sediment transport rates for southern Monterey Bay (Table 2). The total amount of sand reaching the beach from rivers and seacliff retreat is approximately 310,000 m³/yr. That input is not balanced by 40,000 m³/yr blown inland by wind, but the beaches have not been growing annually, so there must be loss to the continental shelf. If we assume that the beaches are not growing, and are in geomorphic equilibrium, then the remainder of the input, 270,000 m³/yr, is probably transported offshore for long-term storage on the continental shelf. Although California beaches typically grow in the summer and thin in the winter, there is apparently a great imbalance in how much sand is transported back to the Monterey beaches once the winter rip tides have moved it offshore. Thornton (2005) suggests that the southern Monterey Bay sand budget is greatly influenced by rip currents that carry sand to offshore storage, and that lateral movement of sand in littoral currents is not as prevalent.

Before 1984, sand mining from the surf zone removed a substantial amount of sand from the coastal sand budget (Table 2). Since 1990, sand has not been extracted directly from the surf zone, but continues to be mined in Marina from a pit just inland from the beach berm (Fig. 23).

Average volume of sand (m ³ /yr)	Sand sources and sinks
	Inputs to the Beach
40,000	Input to the surf zone from the Salinas River
270,000	Input to the beaches from seacliff erosion
	Outputs from the Beach
40,000	Output from wind moving sand into coastal dunes
128,000 (pre 1984) 0 (post 1990)	Historic output from mining sand from surf zone
144,000 (pre-1984) 270,000 (post 1990)	Output from rip tides transporting sediment to permanent(?) offshore storage.

Table 2: Sediment budget details (modified from Thornton, 2005)

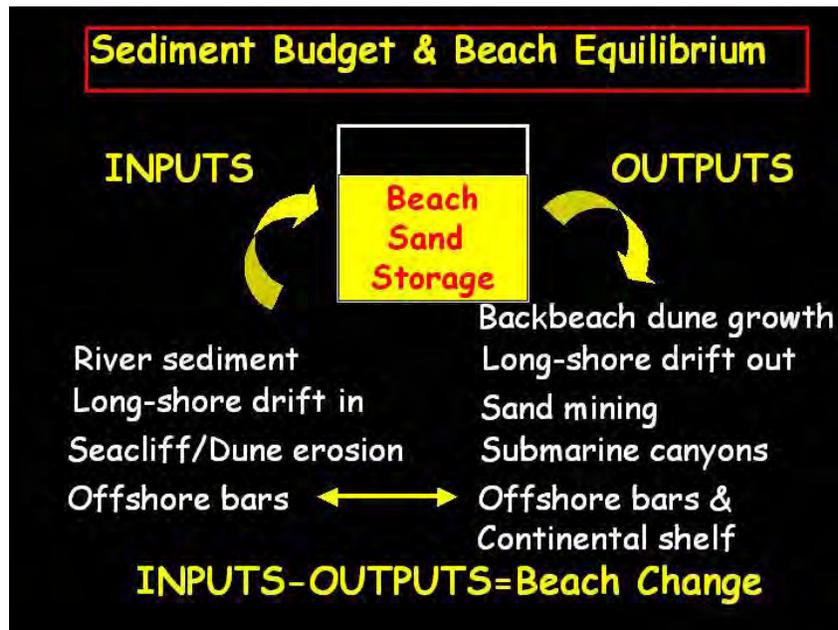


Figure 21: Principal inputs and outputs of sand to the beach along southern Monterey Bay.

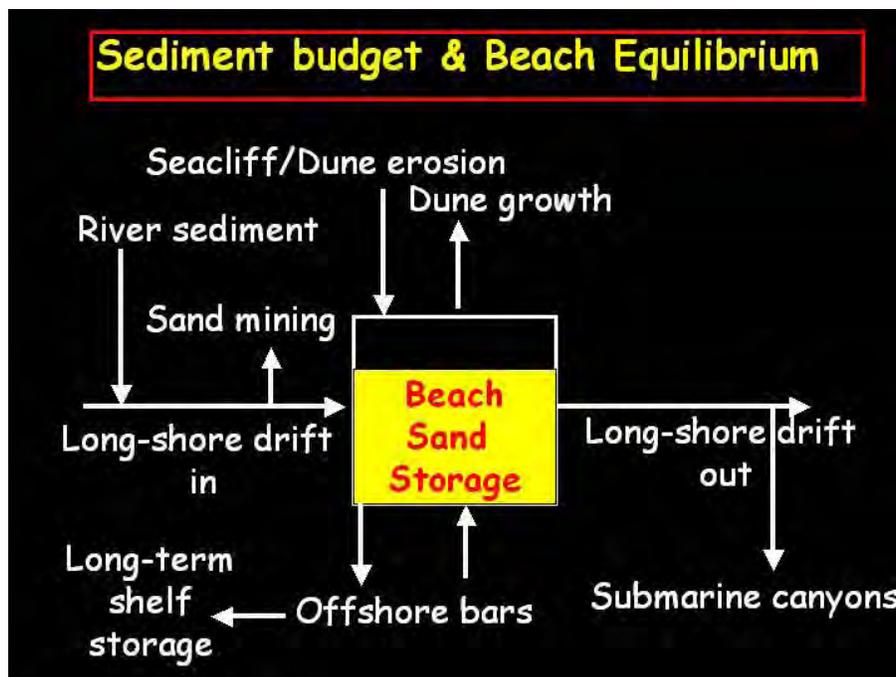


Figure 22: Conceptual systems diagram illustrating the main linkages among inputs and outputs of sand in the beach budget of southern Monterey Bay.

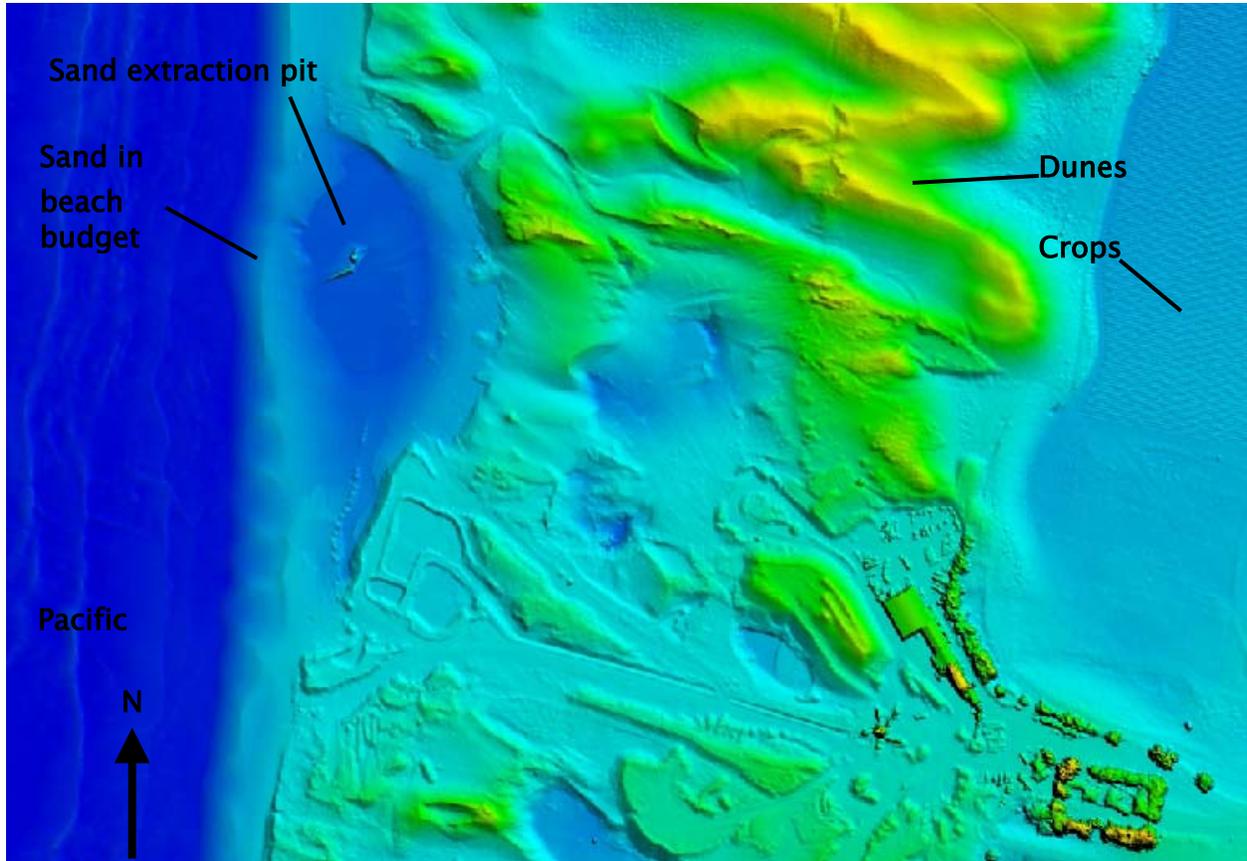


Figure 23: 2004 LIDAR view of sand mining operation located between downtown Marina and the Salinas River. Warm colors are higher elevations. The extraction pit is very close to the active transport zone of the beach. The beach shape is deflected around the western rim of the extraction pit. LIDAR data courtesy of Dave Lott (NOAA, Monterey).

7 Discussion

It is clear that coastal retreat in southern Monterey Bay is a long term process that has been active for the past 18,000 years, and continues unabated today. There is no indication that this natural process will end in the foreseeable future. Even when sea level is held constant, the strong wave energy impacting Monterey Bay (Figure 24) can erode the weak geologic materials composing the coastline. When global sea level again begins to fall, the regional economy will reclaim land now lost to the sea.

Our analysis suggests that there is an obvious conflict in the two coastal management goals of “stable coastlines” and “broad beaches.” In simplistic terms, the broad beaches of Monterey Bay are the result of coastal retreat, which provides the bulk of the sand passing through the beach system. Thus, stabilizing the sea cliffs will doom the beaches.

Four conclusions arise from this analysis.

- 1) The southern Monterey Bay coastline is retreating at approximately 1 m/yr, and has been retreating for a long time. The retreating coastline will continue to impact existing structures and convert both public and private lands to marine continental shelf at a rate of about 1 m/yr. If global change is accelerated by anthropogenic global warming, then the retreat rates will accelerate as well.
- 2) Armoring the coastline would effectively remove the input of sand to the beaches, without reducing the flow of sand from the beaches to offshore storage, which would likely result in smaller or absent beaches.
- 3) Beach nourishment and jetties would likely fail because the local coastline is dominated by rip currents rather than lateral drift.
- 4) Stemming the flow of sand from the beach to offshore storage is an engineering challenge that will generate unforeseeable ecosystem changes in addition to any primary benefits.

The following sections detail the above bullet points. We briefly discuss the advantages and challenges of various management strategies. Other strategies for coastal management may exist, but they do not follow from primary analysis of the coastal sediment system (Figs. 21 and 22), and are not in the scope of this report.

7.1 Letting the Coastline Erode

One coastline management option is to let the coastline erode. This management option does not directly impact the Monterey Bay National Marine Sanctuary. The long term and recent short term coastal retreat rates of southern Monterey Bay are approximately 1 m/yr. If the coastline is left alone, the beaches will likely remain broad, and the retreating coastline will continue to impact existing structures, converting both public and private lands to marine continental shelf at a rate of about 1 m/yr. The local rate of retreat is spatially and temporally



Figure 24: Large surf generated in far off storms occasionally batter the Monterey coastline. On March 9, 2005 a large swell attracted surfers who rode waves with faces up to 55 feet tall off of Pebble Beach, CA. Photo used with permission from Tony Harrington / www.harroart.com.

variable, so local decisions about development restrictions or relocating existing structures should be made with local retreat rate data. The coastline is generally stable near Monterey Municipal wharf, with retreat rates generally increasing to the north toward former Stillwell Hall. The retreat rates will naturally drop if the sea cliff erosion exhumes a harder, less sand-rich geologic formation, or climate change brings reduced peak ocean wave energy.

7.2 Armoring the Coastline

Armoring the coastline to reduce coastline retreat rates will result in a loss of sand reaching the beaches, causing the beaches to rapidly shrink as sand stored in the beaches moves offshore. Natural analogs for coastlines with “extensive coastal hardening” exist in Pacific Grove. The resistant granitic rocks that underlie Pacific Grove and the adjacent coastline to the south provides no erodible sea cliff to nourish the sand supply. That lack of sand supply for the coastline results in small, disconnected pocket beaches composed of very coarse sand and gravel (Fig. 25).

There are also examples of “local coastline armoring” at the Monterey Beach Resort, Ocean Harbor House Condominiums, and former Stillwell Hall. Local coastline armoring has resulted in a nascent “peninsula effect,” where the armored portion of the coastline does not erode, but adjacent, natural parts of the coast continue to retreat, leaving the armored portion protruding seaward. This effect is well exemplified in the case of the Stillwell Hall seawall, where the peninsula effect lead to lateral failure of the sea wall (Figs. B1 and B2). Likewise, at highest tides, the beach is now impassable in front of the Monterey Beach Resort (Fig. 26) and Ocean Harbor House Condominiums (Fig. 7). At present, there are still broad beaches fronting both the Resort and Condominiums during most tide conditions, but their adjacent shorelines have respectively experienced 41 m and 14 m of coastal retreat in the past 28 years (Table 1),

leaving these structures at risk. The resulting peninsula effect gradually leaves the armoring more exposed to the force of the ocean and further reduces public beach access. Local armoring without managing adjacent beaches apparently leads to failure of the local armoring project (e.g., Fig. B1).

7.3 Beach Nourishment and Jetties

Beach nourishment will likely fail as a management strategy in southern Monterey Bay because of the natural very high loss of sand to the marine continental shelf. Thornton (2005) emphasizes that the sand in Monterey Bay is rapidly moved offshore by rip currents, with less prevalent lateral movement along the beaches. Thus, jetties, which heavily rely upon littoral drift for success, are also not a likely solution to regional coastal retreat.

Littoral drift brings between 200,000 m³/yr and 250,000 m³/yr of sand and fine gravel from Santa Cruz to the Moss Landing, which is the northern end of the “southern Monterey Bay” study area (Fig. 2; Best and Griggs, 1991). It is unclear whether a significant fraction of that large sediment load historically bypassed Monterey Canyon to feed southern Monterey Bay. Smith et al. (2005) showed that very little sand can presently reach southern Monterey Bay because the northernmost canyon tributary now terminates north of the north jetty of Moss Landing Harbor (Fig. 27). There is presently very little space for sand to bypass north jetty without being directed down the canyon.



Figure 25: Diminutive pocket beaches are present along rocky coastlines where sand supply is low. Rocky coastlines are natural analogs for sea walls and other artificially hardened coastlines.

7.4 Reducing the Loss of Sand to Offshore Storage

The retreat rates, sediment budget, and photos in this report suggest that sand grains in the beach budget have a rapid, one-way transit from the sea cliff, to the beach, and then out to sea for storage on the marine continental shelf. One logical solution is to reduce the loss of sand to the sea, rather than reduce the contribution of sand from the sea cliffs through armoring (Fig. 22). Sand loss can be achieved by reducing the wave energy impacting the coast, with special care to reduce the influence of very erosive El Niño-driven storm waves. Wave energy can be dissipated by engineered offshore structures that dissipate or redirect wave energy. Although the idea is conceptually simple, the engineering of such structures would be challenging and costly in the dynamic Monterey Bay setting. Furthermore, there would be unforeseen and unpredictable consequences in the broader ecosystem of the Monterey Bay Sanctuary since submarine structures strongly affect marine ecosystem function and physical movement of sediment. The unpredictable effects of offshore structures may ultimately be positive or negative.

If offshore structures are successful at reducing wave energy only “locally,” then the locally protected beach would have a lower retreat rate than adjacent beaches, so it would eventually become a peninsula as adjacent shorelines continued to retreat inland. Wave energy refracts to preferentially attack peninsulas, so the structures and locally protected beach would ultimately be subject to attack from the front and sides.



Figure 26: Peninsula effect present at Monterey Beach Resort at very high tides (5.98 ft) and high swells (15.5 ft; 16 second period) of December 9, 2004. Note large rock placed along wall damaged by high seas in December 2002 (Smith, 2005). There is normally a broad beach in front of the Resort, during lower surf and normal tides.

7.5 Coastline Management within the Context of Sea Level Rise

Global sea level will continue to rise an additional few feet during the next 100 years. It is unclear how much of that rise will be anthropogenic and how much will be natural waning of our recent ice age. Given that sea level rise is a virtual certainty, and that coastline retreat is very sensitive to the position of sea level, Monterey Bay will experience perennial coastal retreat. The challenges associated with stabilizing this dynamic, high-energy coastline, and the likelihood of unforeseen physical and ecological results of an engineering approach, dictate that a realistic cost-benefit analysis will include the cost of adaptive management, periodic maintenance, and eventual decommissioning in case desired results are not achieved, environmental impacts become unacceptable, or the project success becomes diminished by sea level rise.

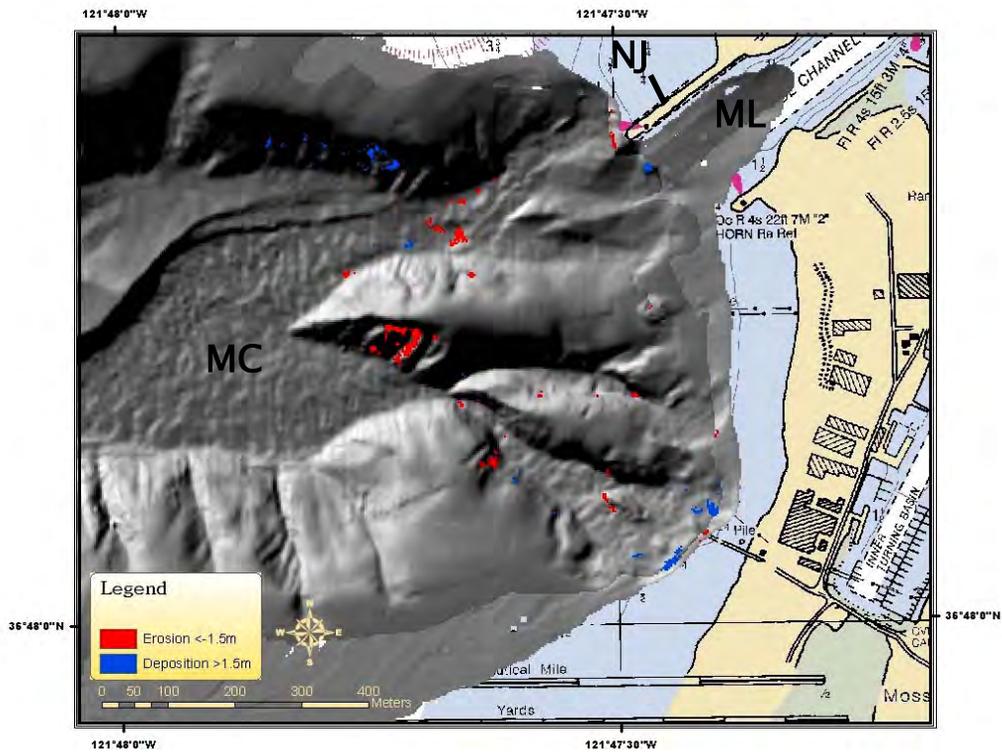


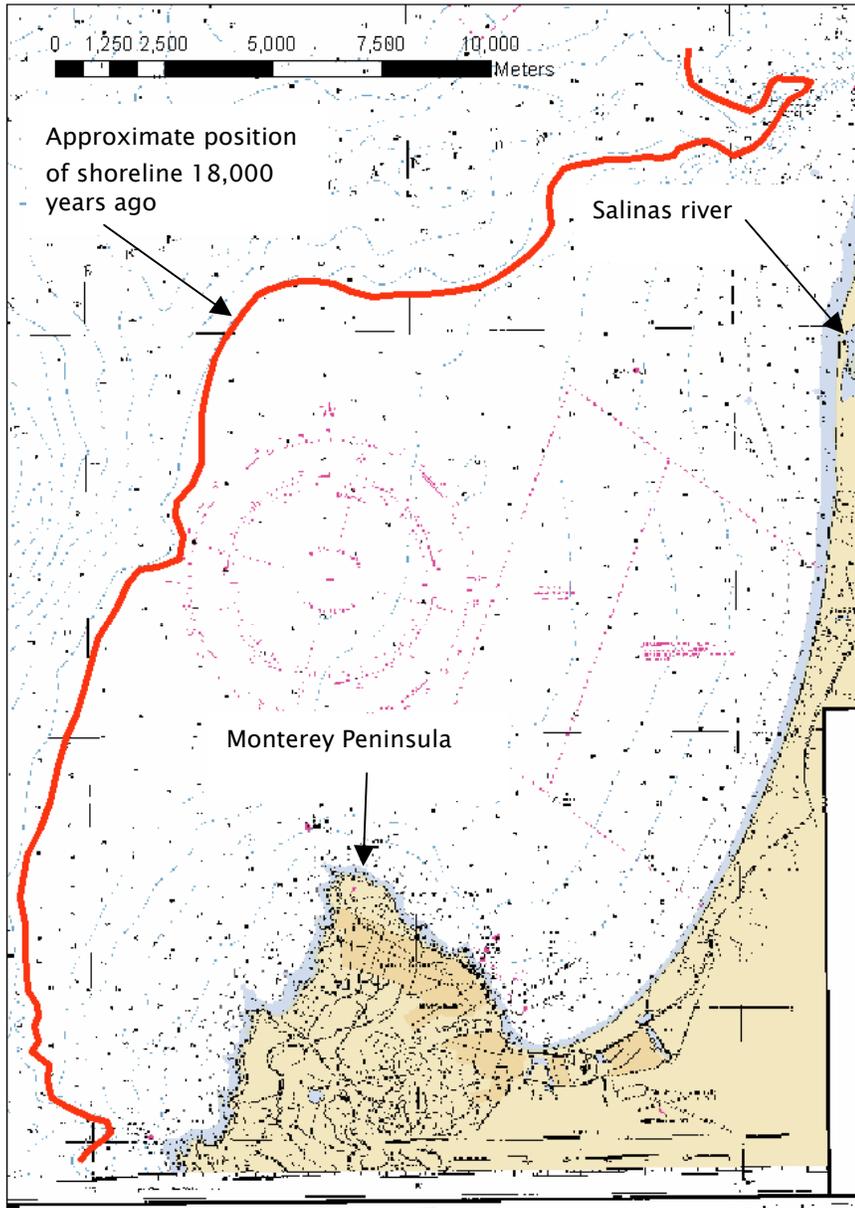
Figure 27: Digital shaded relief image of the head of Monterey Canyon (MC). Northernmost tributary to the canyon is located north of the Moss Landing Harbor (ML) north jetty (NJ). See Figure 2 for location. 2004 Data from the CSUMB Seafloor Mapping Lab. Digital image from Astilla (2005).

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9 Appendix A: Bathymetric Chart



NOAA nautical bathymetric map. The red line is drawn at 130 m (71 fathoms) water depth, the 18,000 year old shoreline.

10 Appendix B: Miscellaneous Oblique Aerial Photographs



Figure B1: Stillwell Hall in 2003 showing sea wall compromised by unrestricted retreat of adjacent sea cliffs. This photo illustrates the “peninsula effect” produced by local hardening of a retreating coastline. Note sand cones and sand aprons transferring large volume of sand from sea cliff to beach.



Figure B2: Stillwell Hall on October 31, 2004 showing site after building and seawall were removed.



Figure B3: Historic storm drain(?) outfall exposed by many meters of recent coastal retreat adjacent to sea wall at Ocean Harbor House Condominiums. December 9, 2004.



Figure B4: Ocean Harbor House Condominiums on October 31, 2004 showing site after large rock was placed to create a sea wall.



Figure B5: Monterey Beach Resort on October 31, 2004.



Figure B6: Sea wall at end of Tioga Avenue, October 31, 2004.



Figure B7: Close up of sea wall at end of Tioga Avenue, October 31, 2004.



Figure B8: Storm drain outfall on Former Fort Ord compromised by coastal retreat. Canyon is formed by rapid undercutting and vertical failing of buried storm drain pipe (see Fig. B9). Photo by David Norris September 2002. See Figure 18 for map view of the eroded canyon.



Figure B9: Storm drain outfall on Former Fort Ord compromised by coastal retreat. Waterfall undercuts weak sandstone substrate causing subsequent collapse of storm drain pipe sections. (see Fig. B9 for original location of outfall). Photo by David Norris September 2002. See Figure 18 for map view of the eroded canyon.

11 Appendix C: Assessment of Aerial LIDAR Precision and Accuracy

Preliminary accuracy assessment of recent LIDAR data at Elkhorn Slough (11/15/04)

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Elkhorn Slough LIDAR data are elevations of georeferenced, 1 m x 1 m pixels. We assessed the accuracy and precision of the pixel elevations by direct comparison with accurate and precise elevations obtained with RTK-GPS and laser total station.

Methods

The total station data were registered to NAVD88 using the RTK-GPS. Following that vertical registration, RTK-GPS elevations and total station elevations were in close agreement, usually less than 2 cm difference, on subsequent readings on a variety of targets. Therefore, we consider both the RTK-GPS and total station estimates of elevation to be comparable in quality. The following analysis includes 91 independent comparisons between survey point elevations and LIDAR pixel elevations in the region near Kirby Park in Elkhorn Slough. The variate being analyzed is "LIDAR" minus "survey," so a significant positive bias in the variate would indicate an accuracy error with the LIDAR values too high on average.

Results

Table C1 shows that the full range of difference values is approximately ± 1 m. However most of the differences were surprisingly close to 0 m (Figure C1), the average difference is positive 5 cm. The 95% confidence bounds on the mean difference include the value 0 m, indicating reasonable accuracy in the LIDAR data (Table C1).

An R^2 of 0.95 indicates a high degree of correlation between the LIDAR and survey elevations (Fig. C2). The best fit line has a slope of 0.92, slightly below a value of 1.0, which would have indicated perfect accuracy. The 95% confidence limits on the slope span 0.88 to 0.97, so the slope is significantly different from 1.0. The low slope suggests a slight bias toward low LIDAR values. However, Figure C2 contains a single high value point that may be heavily leveraging the results. When the single leverage point is removed, the R^2 value is still a very significant 0.93, but the slope value now ranges from 0.89 to 1.0, using 95% confidence limits. This further step suggests that there is no significant bias (accuracy error) in the LIDAR elevation data.

Table C1: Descriptive statistics of LIDAR-SURVEY (meters)

Mean	0.052495
Standard Error	0.027313
Median	0.055
Mode	0.175
Standard Deviation	0.260551
Sample Variance	0.067887
Kurtosis	6.607241
Skewness	-0.90769
Range	2.041
Minimum	-1.159
Maximum	0.882
Sum	4.777
Count	91
Confidence Level (95.0%)	0.054262
Upper 95% bound	0.106757
mean	0.052495
Lower 95% bound	-0.00177

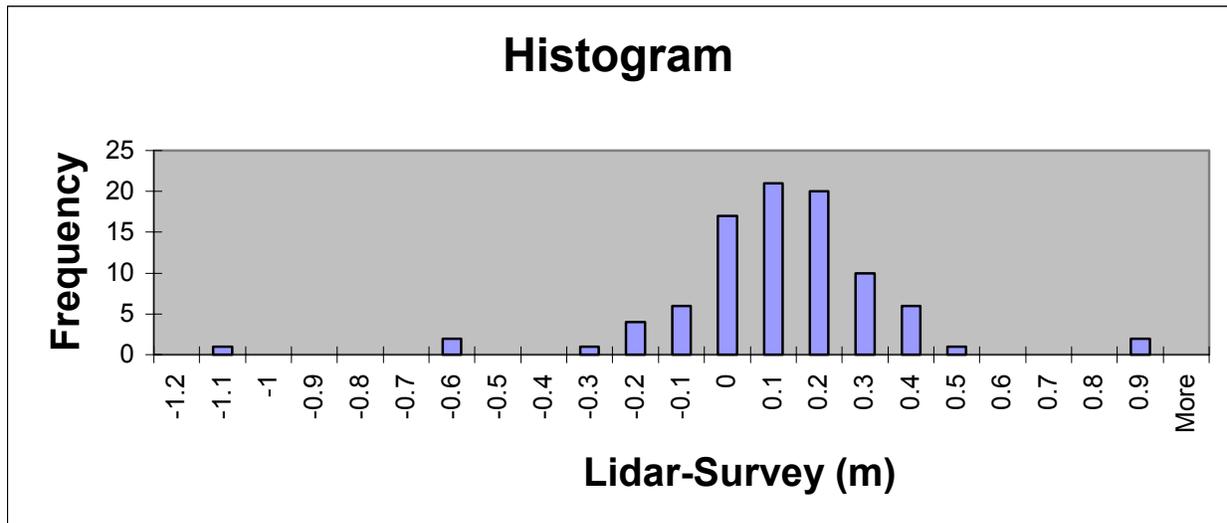


Figure C1: Distribution of differences between LIDAR pixel elevations and survey elevations.

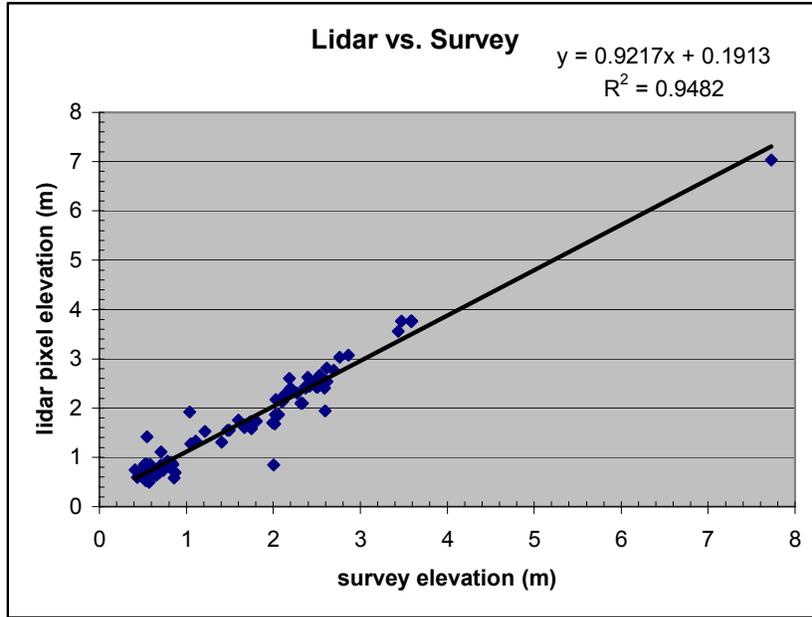


Figure C2: Scatterplot of LIDAR and survey elevations.

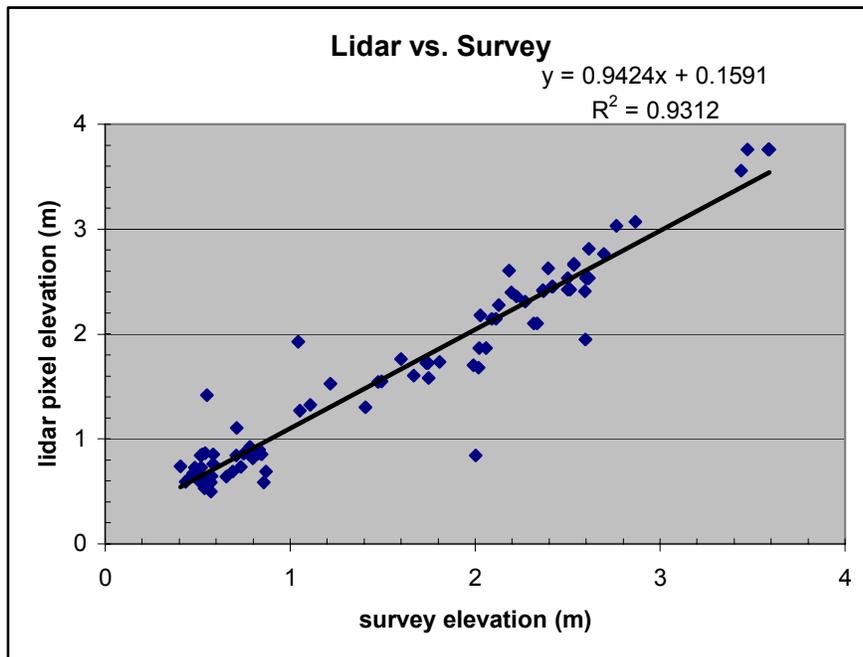


Figure C3: Scatterplot of elevation differences with leverage points removed.

