



**A PILOT STUDY FOR THE LONG-TERM VOLUMETRIC
SEDIMENT CONTRIBUTION FROM LANDSLIDES: BIG
SUR COASTLINE, CALIFORNIA**

by

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INTRODUCTION

The 1997-98 El Niño brought very high amounts of precipitation to California's central coast, raising groundwater levels and destabilizing slopes throughout the region. A number of large landslides in the coastal mountains of Big Sur in Monterey and San Luis Obispo counties blocked access along California's Highway 1, closing the highway for several months. Large slope failures along the Big Sur coast section of Highway 1 occur frequently due to the steep topography and weak bedrock (Figure 1). Major landslides occurred in the severe winter months of 1972, 1978, 1983, 1989, and 1998 (Cleveland, 1973; Works, 1984). A large slope failure in 1983 resulted in the closure of Highway 1 for over a year for repairs and slope stabilization. Highway repairs as a result of the 1983 landslide cost over \$7 million and generated a combined three million cubic yards of debris from landslide removal and excavations for highway realignment (Engellenner, 1984). In 2000, a year with near average rainfall, two landslides resulted in the closure of Highway 1 for weeks at a time.



Photo courtesy of Caltrans

Figure 1: Large-scale landslides are common along the Big Sur coast and road closures from slides are a routine occurrence.

The California Department of Transportation (Caltrans) is responsible for maintaining this precarious highway corridor and providing prompt and safe access for both local residents and tourists. Prior to the 1998 storm season, a typical road opening measure involved some disposal of landslide material and excess material generated from slope stabilization measures on the

seaward side of the highway. This disposed material, either directly, or indirectly through subsequent erosional events, was eventually transported downslope into the adjacent ocean waters. In addition to the landslides that initialize above the road, slope failures also occur on the steep slopes below the road. This natural process delivers sediment to the base of the coastal mountains where the material is eroded and dispersed by waves and nearshore currents. As a result, any coastal slope landslide, whether through natural processes or anthropogenic means, can result in sediment entering the littoral zone.

The waters offshore of the Big Sur coastline are part of the MBNMS (Figure 2), which was established in 1992. MBNMS staff became concerned with the Caltrans landslide disposal practices for three reasons: 1) National Marine Sanctuary regulations prohibit disposal of material within a Sanctuary or where it will enter a Sanctuary; 2) landslide disposal practices have the potential to bury shoreline habitat, converting marine habitats from rocky substrate to soft bottom; and 3) the disposal practices have the potential to increase nearshore suspended sediment concentrations, possibly impacting coastal biological communities. On the other hand, coastal landslides and streams naturally deliver sediment to the coast providing nutrients to the water as well as material for beaches.

This study characterizes the long-term sediment contributions from landslides along the approximately 120-km-long Big Sur coast in Monterey and San Luis Obispo counties from south of the Carmel River to San Carpoforo Creek (Figure 2). The geographic limits of the study correspond to that portion of the coast where the steep slopes of the Santa Lucia Mountain Range plunge uninterrupted to the Pacific Ocean. The primary research goals are to quantify the historic volume of sediment that enters MBNMS through coastal landslide processes and to assess the spatial distribution of volume losses and gains using historical and recent aerial stereo photographs. The results are essential for the development of a management plan for Highway 1 that strives to maintain this highly scenic corridor while minimizing adverse impacts on nearshore biologic communities. The focus on quantifying the long-term average annual sediment yield to the littoral system from coastal slope failures and examining the spatial distribution of volumetric losses will provide an increased understanding of the relationship between the geology of the region and the pervasive landslide processes.

STUDY AREA

The Big Sur coastline lies on the western boundary of the Coast Ranges geomorphic province, a northwest trending series of mountains and valleys flanking the coast from near Santa Barbara, CA to the Oregon border. In the Big Sur area, the Santa Lucia Mountain Range, part of the Coast Ranges, dominates the landscape. The mountains rise from sea level, reaching elevations of nearly 1600 m within five km of the coast, making this one of the steepest coastal slopes in the conterminous United States.

The Santa Lucia Range is composed primarily of sheared and metamorphosed sedimentary rocks of the Franciscan Formation, and granitic and metamorphic rocks of



Figure 2: Map showing location of the MBNMS and the Big Sur coast in central California

the Sur Complex (Dibblee, 1974; Ross, 1976; Hall, 1991). The contact between these geologic units is the Sur-Nacimiento fault, part of the northwest trending San Andreas Fault system. The rocks of the Franciscan Formation tend to be weaker than those of the Sur Complex; therefore, the majority of the chronic landslides occur where the steep slopes are underlain by Franciscan Formation rocks. However, the lithology within the Franciscan Formation varies dramatically, and the softer, highly sheared rocks and mélangé are more prone to landsliding while the various sedimentary strata and volcanic rocks form somewhat more stable slopes.

METHODS

The primary tools employed in this study are digital photogrammetry and GIS. Historical and recent vertical aerial photography are processed using digital photogrammetry to produce Digital Terrain Models (DTMs) from 3D stereo models. GIS is used to calculate volume changes and to assess the spatial distribution of the terrain changes. The historical photography is from 1942 (1:30000) and the recent photography was collected in 1994, at a 1:24000 scale. These photographs provide a base for determining a 52-year end-point volumetric change rate for two pilot study areas.

The process of digital photogrammetry requires a specific workflow that results in the production of orthophotographs (digital images from which all distortions have been removed). The distortions inherent in unrectified photography are those related to the camera system, the camera position, and displacements associated with the amount of terrain relief in the area (Falkner, 1995). Once these distortions are removed, the resulting images are orthorectified and can be used to make accurate measurements. In the processing, ground control points are used to tie the imagery to real-world coordinates. A DTM is required to completely remove the effects of relief distortion. The DTMs are built from the stereo images using a TIN (Triangulated Irregular Network) of elevation points rather than a standard grid model in order to best capture the steep and rapidly changing topography.

Once the TIN models are generated, the topographic surfaces from the two dates are subtracted to produce an overall volume change, calculated from a datum of 1.5 m above mean sea level. The 1.5 m elevation represents the lowest elevation that photogrammetric stereo models can confidently derive elevation without significant visual interference from the movement of waves on the water or in the swash zone on the beach (Hapke and Richmond, 2000). Mosaics created from the orthophotographs are used in conjunction with the volumetric change to map locations and spatial distribution of historically active landslides. The orthophotomosaics are also used to determine whether the material has been completely lost to the littoral system or whether some volume is stored on land at the base of the slope. The downslope areas where deposition of landslide debris has taken place from the older to the more recent photos show up in the topographic comparisons as areas of volume gain.

RESULTS AND DISCUSSION

Two pilot study areas were chosen in order to test and refine the processing techniques and data analysis for the study. These locations, near Wreck Beach and Lopez Point, are shown on figure 2. Both pilot areas are underlain by the Franciscan Formation but the Wreck Beach pilot area is underlain by more resistant sedimentary strata while the Lopez Point pilot area is located within intensely sheared metasedimentary rock and paleo-landslide deposits. Each pilot area was demarcated by identifying from the stereo photography those portions of the coastal slope that show evidence of active landsliding and where the eroded material would have a direct pathway to the ocean at the base of the slope. The two pilot areas are outlined on the orthophotographs in figure 3. The Wreck Beach pilot area is 1.3 km², and extends along approximately 2.5 km of coastline; the Lopez Point pilot area is 2.2 km² and extends along an approximately 5.2 km stretch of coastline (Table 1). Highway 1 passes directly through the Lopez Point pilot area, but is several hundred meters inland of the Wreck Beach pilot area.

The rate of volume change (net loss in both cases) is calculated over a period of 52 years. Since the pilot areas differ in size, the results are presented as m³ normalized to the km² of each area (Table 1). As shown in Table 1, the volumetric loss rate in these two areas differs by more than an order of magnitude. As described above, the geology differs dramatically in these two areas; the northern pilot area (Wreck Beach) is dominated by sandstones and graywackes while the southern pilot area (Lopez Point) is located in weaker materials, including ancient landslide deposits and sheared metavolcanic rocks (Hall, 1991). The existence of a significant embayment of the coast beginning at Lopez Point (figure 2) is further evidence that the material along this portion of the coastline is less resistant and erodes at a faster rate than the Wreck Beach pilot area to the north.

Table 1: Pilot Area Data

	Area (km ²)	Linear extent along coast (km)	Volumetric Loss Rate (m ³ /km ² /yr)
Pilot Area #1	1.32	2.5	2.8x10 ³ ± 0.15x10 ³
Pilot Area #2	2.17	5.2	77.4x10 ³ ± 6.4x10 ³

Error Analysis

The error in the volume calculated for each date is a function of rectification errors, errors associated with the accuracy of the DTM and accuracy of the imagery based on the pixel resolution. The source of the rectification error is the error inherent to vertical aerial photography, including those associated with the camera system, the aircraft attitude, and topography. The rectification software incorporates these errors into the RMS error of the photogrammetric processing workflow. Error associated with the accuracy of the DTM is a function of the scale of the stereo photography (Ackerman, 1996). Finally, error associated with the pixel resolution is directly related to the resolution at which the photographs are scanned; this is simply the visual limitation of identifying an object (or location) that is smaller in dimension than the pixel size of the digital image. Using standard statistics, the error, or variance, associated with the TIN model for each date is determined by:

$$E_t = [(e_r)^2 + (e_d)^2 + (e_p)^2]^{0.5} \quad (1)$$

where e_r = rectification error; e_d = dtm error; e_p = pixel resolution; and the subscript t is a given time, or date, from which the data are derived. This surface error is translated to an uncertainty in volume by assessing the calculated error over the area within which the volume was calculated:

$$E_{vt} = (E_t * A)/V_t \quad (2)$$

Where A is the area under which the volume was calculated and V_t is the volume calculated for a particular date. This equation produces a percent volume of the total calculated volume that is within the uncertainty range for that date of data. In order to determine the total error in the

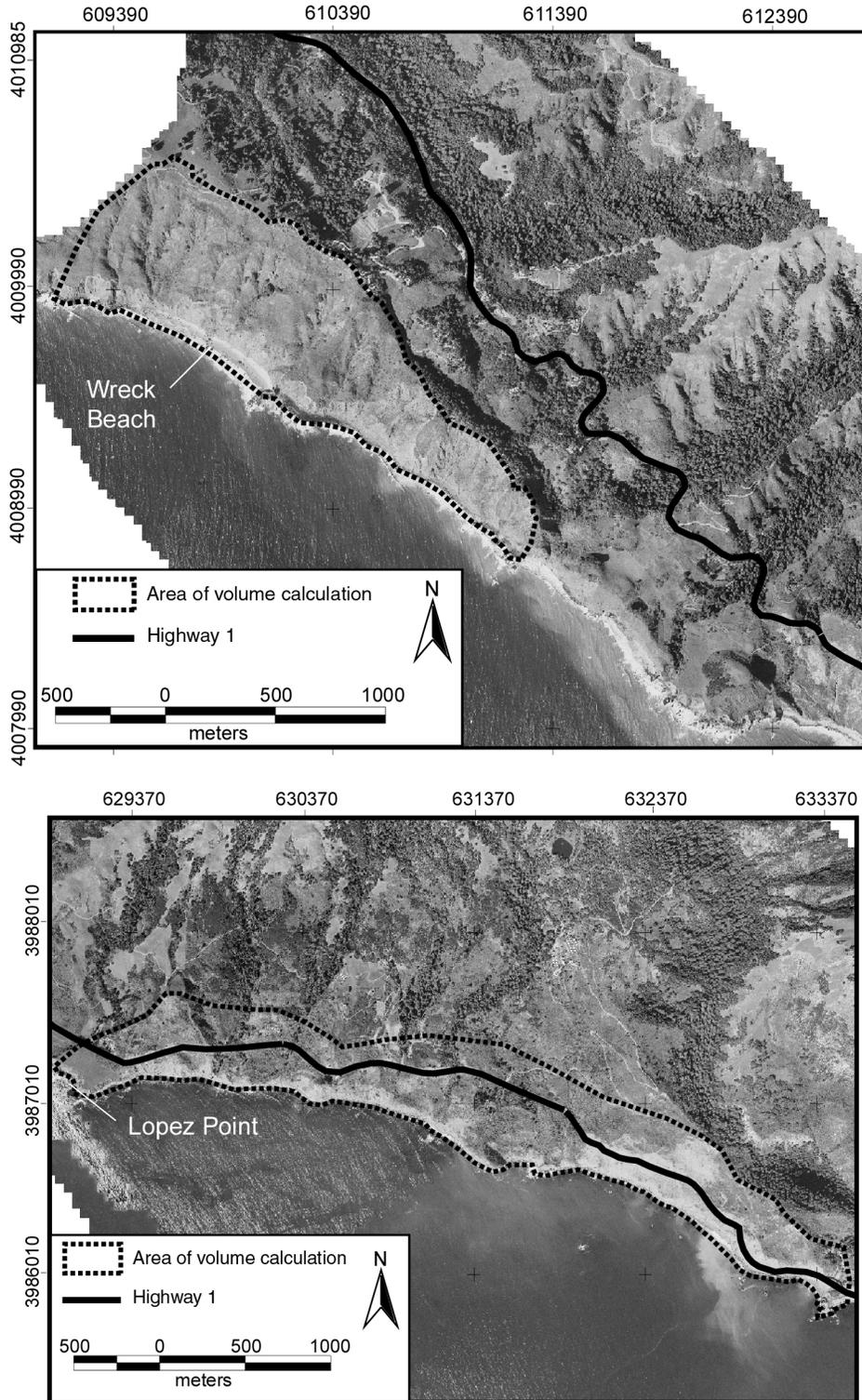


Figure 3: Orthophotomosaics of Wreck Beach (top) and Lopez Point pilot study areas (bottom). The areas within which volumes were calculated are shown as dashed polygons.

volume change calculation, the uncertainties for the two dates for a given area are summed:

$$Total\ error = E_{v1994} + E_{v1942} \quad (3)$$

For each pilot area, the uncertainty for the historic (1942) volume was higher than for the recent (1994) volume; this is primarily due to the smaller scale photography and the higher RMS from the rectification processing. The total errors in the volume change calculations associated with the pilot areas are 3.3% (Wreck Beach area) and 4.7% (Lopez Point area).

Contours of TIN Subtraction

In order to visualize the distribution of volume losses and gains in each pilot area, a contoured TIN model of the change (i.e. subtracted surfaces) is created. These contours are plotted on the draped surface of the orthophotograph so that the change can be visualized relative to the slope, to variations in slope, and with respect to Highway 1 (Figures 4a and b). The darker grays in figure 4 are areas of volume gain; the lighter grays represent areas of volume loss.

In Figure 4a (Wreck Beach pilot area), there is evidence that significant landslide material has been retained at the base of the cliffs rather than moved offshore and transported out of the area. Based on the low net volume loss in this area over the past 52 years, it appears that this section of the coast is relatively stable, most likely a function of the underlying sedimentary strata of the Franciscan Formation that are more resistant to erosion and slope failure than other members of the Franciscan Formation.

The volume loss distribution plot within the Lopez Point pilot area (Figure 4b) is dramatically different from the Wreck Beach pilot area, revealing a stretch of coastal slope that is very unstable and prone to landslides with little evidence that material is being stored at the base of the slope. This suggests that the bulk of the volume loss from upslope is transported offshore and removed from the area by nearshore waves and currents. The underlying geology in this area is the Franciscan Formation mélangé and paleo-landslide deposits, both very weak and unstable units. The most active portion of the slope in the Lopez Point pilot area is below the road, with the exception of the region on the east end of the area, called 'Rainrocks' (figure 4b). Debris in this location almost continuously "rains" off the upper slope onto the highway and downslope below the road. Areas of volume gain shown adjacent to the road have been corroborated by Caltrans as being locations of debris stockpile and/or storage of material that awaits permanent disposal.

Discussion

The data presented in this pilot study represent the volumes of material lost from two small sections of the Big Sur coastal slope as calculated between two data sources: 1942 and 1994 aerial photography. While the error analysis and anecdotal evidence support the validity of the findings, it is important to keep in mind that the volume losses are based on a net-loss end-point calculation, and provide little information on the episodicity and timing, and thus processes, of losses and gains within each area. An additional limitation is the somewhat restricted area within which the volumes are calculated. These areas are limited by the available data and the time and resources within which this study was conducted. As described above, the areas of volume

calculations are visually defined by identifying the active slope on the stereo aerial photography. The slope above this area may be historically active, but not in the time span of the two data sets. Therefore, the overall rate calculated is restricted to the time period (52 years) of this study and may vary in the long or short-term.

CONCLUSIONS

The long-term volumetric sediment contribution to the littoral system from coastal landslides can be quantified using aerial photography processed with digital stereo photogrammetry to produce TIN models of the terrain for different years. The TIN models can be subtracted from each other to quantify the net volume change for a given area; volume gains and losses can be plotted as contours of change to assess the change distribution. This technique of dynamic landscape modeling provides valuable information regarding the variability in magnitude and distribution of sediment entering the littoral system that can be useful for the management of landslide material in an environmentally sensitive and remote portion of the central California coast.

Pilot studies completed for two areas exemplify the dramatic variation in volumetric loss rates in an area where the complex geology results in a variety of lithologies being exposed along the coastal slope. Where the slope is formed in resistant interbedded sandstones and siltstones, the volumetric loss rate is nearly thirty times smaller than the volumetric loss rate in an area underlain by highly sheared metasedimentary rocks and mélangé.

The results of this study will aid Caltrans and the MBNMS with the evaluation of existing practices of landslide debris disposal along the Big Sur Highway 1 corridor and the development of new management practices designed to minimize environmental impacts.

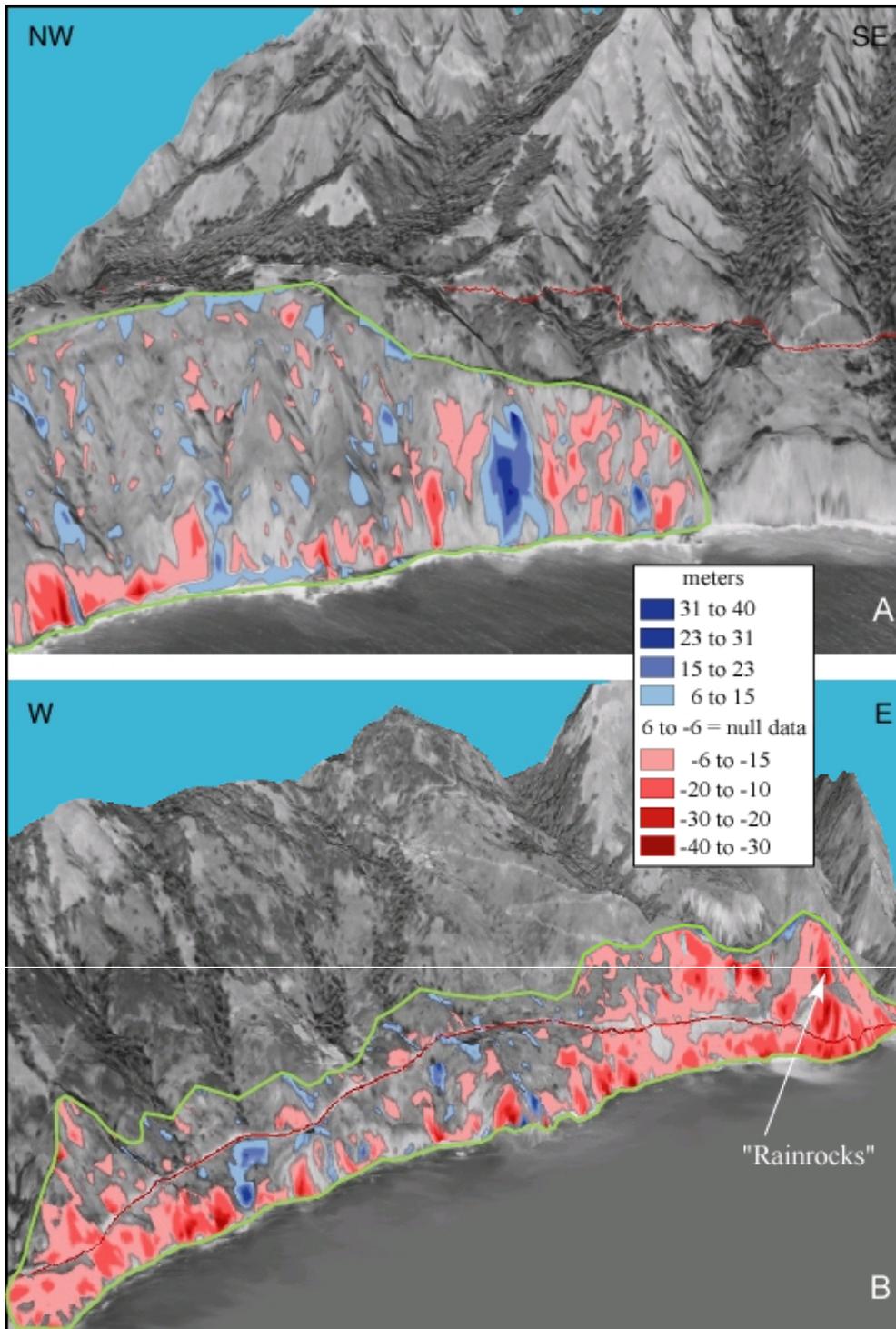


Figure 4: Elevation difference map of the two pilot areas. Reds are elevation losses and blues are elevation increases; the elevation difference is overlain on the draped orthophotographs of the northern (top) and southern (bottom) pilot areas. The green polygon outlines the area over which the elevation difference was determined. Highway 1 is shown as the dark red line.

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