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Documenting a Century of Coastline Change along Central California and Associated Challenges: From the Qualitative to the Quantitative

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Abstract: Wave erosion has moved coastal cliffs and bluffs landward over the centuries. Now climate change-induced sea-level rise (SLR) and the changes in wave action are accelerating coastline retreat around the world. Documenting the erosion of cliffed coasts and projecting the rate of coastline retreat under future SLR scenarios are more challenging than historical and future shoreline change studies along low-lying sandy beaches. The objective of this research was to study coastal erosion of the West Cliff Drive area in Santa Cruz along the Central California Coast and identify the challenges in coastline change analysis. We investigated the geological history, geomorphic differences, and documented cliff retreat to assess coastal erosion qualitatively. We also conducted a quantitative assessment of cliff retreat through extracting and analyzing the coastline position at three different times (1953, 1975, and 2018). The results showed that the total retreat of the West Cliff Drive coastline over 65 years ranges from 0.3 to 32 m, and the maximum cliff retreat rate was 0.5 m/year. Geometric errors, the complex profiles of coastal cliffs, and irregularities in the processes of coastal erosion, including the undercutting of the base of the cliff and formation of caves, were some of the identified challenges in documenting historical coastline retreat. These can each increase the uncertainty of calculated retreat rates. Reducing the uncertainties in retreat rates is an essential initial step in projecting cliff and bluff retreat under future SLR more accurately and in developing a practical adaptive management plan to cope with the impacts of coastline change along this highly populated edge.

Keywords: coastline; cliff and bluff retreat; erosion rate; uncertainty; sea-level rise; adaptive management

1. Introduction

Many diverse natural forces and processes interact along the shoreline, making the coastline one of the world's most dynamic environments [1–3]. Waves, tides, wind, storms, rain, and runoff combine to build up, wear down, and continually reshape the interface of land and sea [3–5]. Through the 20th century, however, global sea-level rise, due in a large part to human-induced climate change [6–8], contributed to increase both cliff and beach erosion [9,10]. Coastline (cliff and bluff) erosion (covered in this study) is different from shoreline (beach) erosion and is defined as the actual landward retreat of a cliff or bluff. While a number of older references indicate that cliffs occur along about 80% of the world's coasts [10–12], more recent work using a GIS-based global mapping analysis and a detailed literature review suggest that coastal cliffs likely exist on about 52% of the global shoreline [13]. Cliff retreat is distinct from beach erosion in that it is not recoverable, at least within our lifetime, by any natural processes [10]. The terms cliff and bluff are often used interchangeably [10,14], but in this study cliff refers to coastal landforms that consist of harder and more resistant rocks that stand higher and steeper than bluffs, which are generally composed of weaker materials and stand at gentler slopes (Figure 1) [10].

Figure 1. (**a**,**b**): Coastal cliffs, (**c**,**d**): Coastal bluffs. Photos: © 2002-2015, California Coastal Records Project [15].

The world's coastlines will respond to global climate changes and the associated adjustment to oceanographic forcing [16]. For cliffed coasts with limited beach development, there appears to be a relationship between long-term cliff retreat and the rate of sea-level rise [17]. Satellite altimetry has shown an average rise in global mean sea level (GMSL) of ~3.4 mm/year since 1993 [10,18,19] and this rate is increasing by about 0.08 mm annually, which implies that global mean sea level could rise at least 65 ± 12 cm by 2100 compared with 2005 [20], enough to cause significant problems for coastal cities around the planet [21]. However, more recent studies along California's coastline indicate the possibility of significantly higher sea levels by 2100, with levels at specific future dates highly dependent on future global greenhouse gas emissions [22]. Future sea-level rise will increase the frequency at which waves will attack the base of coastal cliffs and bluffs [23–28], and as a result, coastal erosion will almost certainly be accelerated during the 21st century [23,27,29]. In addition, changes in regional meteorological and climate patterns, including the frequency and intensity of El Niño events, coupled with rising sea level, are predicted to result in increasing extremes in sea level [30] and wave power [31]. Waves riding on these higher water levels will cause increased coastal erosion and shoreline damage, more than that expected from sea-level rise alone [30]. Many major coastal cities were developed in areas vulnerable to shoreline and/or coastal erosion [32]. With coastal populations and associated economic assets continuing to increase [33], cliff, bluff top, and shoreline development will be increasingly threatened by erosion and retreat [34]. This has led to an increased need for accurate information on rates and trends of coastal recession [35] in order to respond and adapt to expected future shoreline changes.

In this study, we focused on California's coast, which is experiencing well-documented sea-level rise [22,36] and related coastal impacts including coastal erosion [10,30,37]. California's coast reflects a complex geological history and the interplay of tectonic or mountain building processes, geology, climate, and the sea, and has always been identified with change [1,38]. At the close of the last ice age 18,000 years ago, the coastline stood several to as far as 50 km offshore to the west [4]. As the climate warmed, seawater expanded and ice melted. In response, sea level rose about 130 m and advanced inland, moving the cliffs, bluffs, and beaches eastward. About 8000 years ago, the rate of sea-level rise slowed from an average of about 11mm/year over the previous 10,000 years to less than a millimeter per year. Over the past century or so, however, due primarily to anthropogenic global warming, the global rate of sea-level rise has accelerated to about 3.4 mm/year (13.4 inches/century) leading to an increase in rates of shoreline and coastline retreat.

The great majority (72% or about 1272 km) of California's 1760 km coastline consists of actively eroding sea cliffs and bluffs [4], and of the 1272 km cliffed coast—including the 5.8 km (3.6 mile) long section of Santa Cruz coast covered in this paper—about 1040 km consists of low to moderate relief cliffs and bluffs ranging in height from about 10 to 100 m, which are typically eroded into uplifted marine terraces (Figure 2). Some cliff rocks are so hard and resistant, however, that photographs taken of the coast 75 years ago look identical to those of today. Elsewhere, however, coastal bluff materials are so soft and weak that the coast is being eroded at average rates of 2 m or more each year. These changes are easily recognized when comparing historic ground photographs.

Figure 2. Typical morphology of much of California coast with cliffs eroded into an uplifted marine terrace (photo by Gary Griggs, 2006).

The coast of California is dominated by uplifted marine terraces fronted by low cliffs, but also includes steep coastal mountains and areas of coastal lowlands, estuaries, and dunes [30]. The two sea-level rise related hazards of greatest concern to any oceanfront development along the California coast, whether public or private, are (1) coastal cliff and bluff erosion (Figure 3a) and (2) more frequent flooding of low-lying areas by storm waves and high tides (Figure 3b), followed in time by permanent inundation [39]. California's coastline is approaching a crisis point, which has resulted from a combination of natural processes and cycles, combined with human intervention and population growth [10]. California's population and economic centers are concentrated along its coast [40]. Although California's 19 coastal counties (including San Francisco Bay) make up only 22% of the state's land mass, they account for 68% of its population [41], 80% of its wages, and 80% of its GDP [42]. In addition, California's coastal population is expected to continue to grow significantly over the coming decades [43], which will only compound the erosion and flooding problems at the edge. A recent study [27], showed that for California, the world's 5th largest economy, over $150 billion in property, equating to more than 6% of the state's GDP and 600,000 people, could be impacted by coastal flooding by 2100.

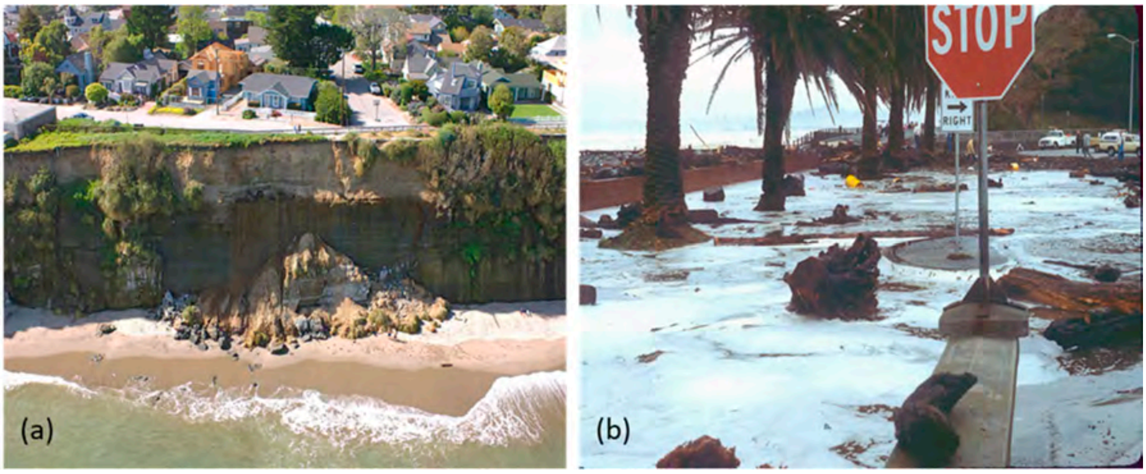

Figure 3. (**a**) The erosion of a coastal cliff has removed an ocean front street about 10 km from the project site. (**b**) Flooding of a coastal parking lot during a period of elevated sea level and large waves approximately 20 km from the study area.

2. Study Area

The West Cliff Drive coastline, which has been selected as a case study in this paper, extends 5.8 km along the western edge of the city of Santa Cruz between Point Santa Cruz and Natural Bridges State Beach on the central California coast (Figure 4). This section of the coastline is somewhat unique in California in having a public street (West Cliff Drive) extending the entire 5.8 km (3.6 mile) length, along with a pedestrian/bicycle path. This allows unobstructed views of this dramatic coast without the presence of homes or other development on the top of bluff, which is more typical of many of the state's coastal communities. As a result, this road has been a popular area for residents and visitors alike for well over a century.

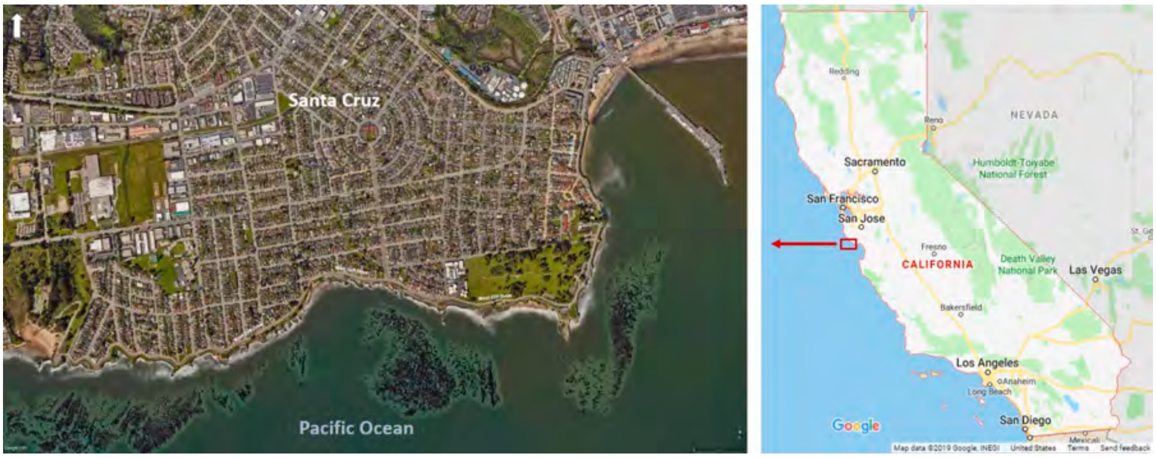

Figure 4. West Cliff Drive study area.

2.1. Geologic Setting

The striking features of California's diverse landscape, the San Andreas Fault (which lies just 25 km east of the project area) and its associated earthquakes, the rugged coastal mountains, and the uplifted marine terraces [36] and coastal cliffs that characterize much of the coastline, all have their origins in millions of years of large-scale tectonic processes that continue today [4]. The rocks exposed along the coastline and in the sea cliffs provide evidence of this complex geological history and the changes the landscape has undergone. Coastal cliffs along the state's coast may consist of granitic, volcanic, metamorphic, or sedimentary rocks.

The West Cliff Drive coastline consists of near vertical cliffs varying in height from about 6 to 12 m (20 to 40 feet), which form the outer edge of the lowest uplifted marine terrace along this coast (Figure 5a). The lower bedrock portion of the seacliff consists of two different geologic units: The older, harder, and more resistant Santa Cruz Mudstone of Miocene age (~5–7 million years old; Figure 5a) and the younger and weaker Purisima Formation of Pliocene age (~3–5 million years old) (Figure 6). The mudstone extends approximately 2100 m along the western section of the coastal area studied, while the overlying Purisima Formation makes up the approximately 3700 m long eastern section. The Purisima consists of interbedded mudstones, siltstones, and sandstones that are pervasively jointed. It is the orientation of the joints sets that exerts a major control on the erosion of the bedrock and the shape or morphology of the coastline (Figure 5b). The uppermost 2 to 4 m of the cliffs consist of much younger (~100,000 year old) poorly consolidated, marine and non-marine terrace deposits, primarily sand, gravel, and cobbles (Figure 6). The same processes that formed the coastal landscape continue to act on it today, although at a nearly imperceptible rate. More noticeable, however, is the rate of coastline erosion, as waves attack and undercut the emergent land and force the nearly vertical bluffs to recede inland.

Figure 5. (**a**) Unprotected section of West Cliff Drive study area showing low eroding cliffs eroded into the Santa Cruz Mudstone [15], (**b**) oriented embayments eroded along parallel joints in the Santa Cruz Mudstone (Google Earth, 2018).

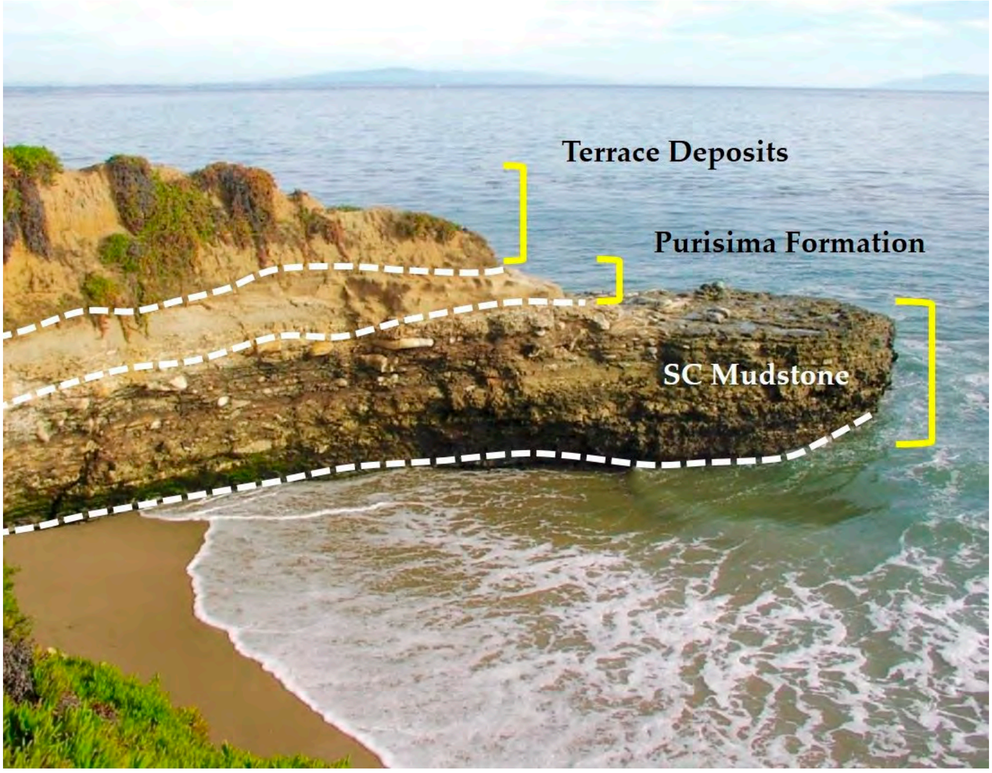

Figure 6. This section of coastal bluff consists of three different geologic units: The Santa Cruz Mudstone, the Purisima Formation, and the overlying unconsolidated terrace deposits, which erode differentially and make selecting a bluff edge subjective.

2.2. *Oceanographic Conditions*

The central California coast experiences a mixed semi-diurnal tide with a maximum range of about 2.5 m (8.2 feet), ranging from +2.0 to −0.50 m (+6.6 to −1.6 feet). During years with strong El Niño events, however, water levels may be elevated as much as 30 cm above predicted water levels for days [30,44], which brings large waves closer to the cliffs, and when coincident with high tides, often produce failure of the bedrock, as well as erosion of the overlying and much more erodible terrace deposits. Current wave conditions along West Cliff Drive were defined using historical data from the Global Ocean Waves database [45] that covers the time period between 1948 and 2008. The offshore wave data was propagated to the shore using the SWAN wave propagation model based on the models developed for California with nearshore bathymetry information [46]. The wave propagation results were used to reconstruct hourly time series of wave parameters (significant wave heights, Hs; and mean periods), as described in Camus et al. [47], and calculate hourly wave energy at the 10 m depth contour along West Cliff Drive. Prevailing winter storm waves approach this stretch of coastline dominantly from the northwest and west and undergo little loss of energy through refraction as they approach the coastline along West Cliff Drive. Significant wave heights of 1 to 2 m occur frequently in the winter months (December through March). During major storms, however, wave heights may reach 4 m or more. This is a high-energy coastline with occasional severe wave attack (Figure 7).

Figure 7. Storm waves at high tide overtopping West Cliff Drive bluff (photos by Gary Griggs).

During the periods of largest waves and highest tides, waves are attacking essentially all of the cliffs along this entire section of coast. About 600 m of the 5800 m long stretch of sea cliffs is buffered by small pocket beaches, which come and go seasonally. These vary in length from about 30 to 300 m with maximum widths of 25–50 m in the summer months. The beaches undergo strong seasonal fluctuations in size in response to changing wave conditions, with sand levels dropping 2 m or more from summer to winter months (Figure 8a,b).

Figure 8. (**a**) Summer and (**b**) winter beach sand levels along West Cliff Drive (photos by Gary Griggs).

The mean and 25% and 75% percentiles of annual wave energy, and corresponding directions were then calculated using the hourly time series. There is significant variation in a high percentile of wave heights (95% percentile of significant wave height, Hs95) and wave energy intensity and direction (Figure 9). Annual mean wave energy decreases from west to east and rotates slightly anticlockwise (Figure 9a). Changes in wave energy (Figure 9b) are more marked than the differences in high-values of wave heights (Figure 9c). This is because annual wave energy not only represents conditions of a single storm, but, in addition, high wave conditions accrue proportionally more energy than calmer sea states [31]. Therefore, wave power not only shows a significant spatial variation across West Cliff as a result of wave propagation, but may also serve as an indicator of erosion potential of wave action on the cliffs over cumulative periods of time.

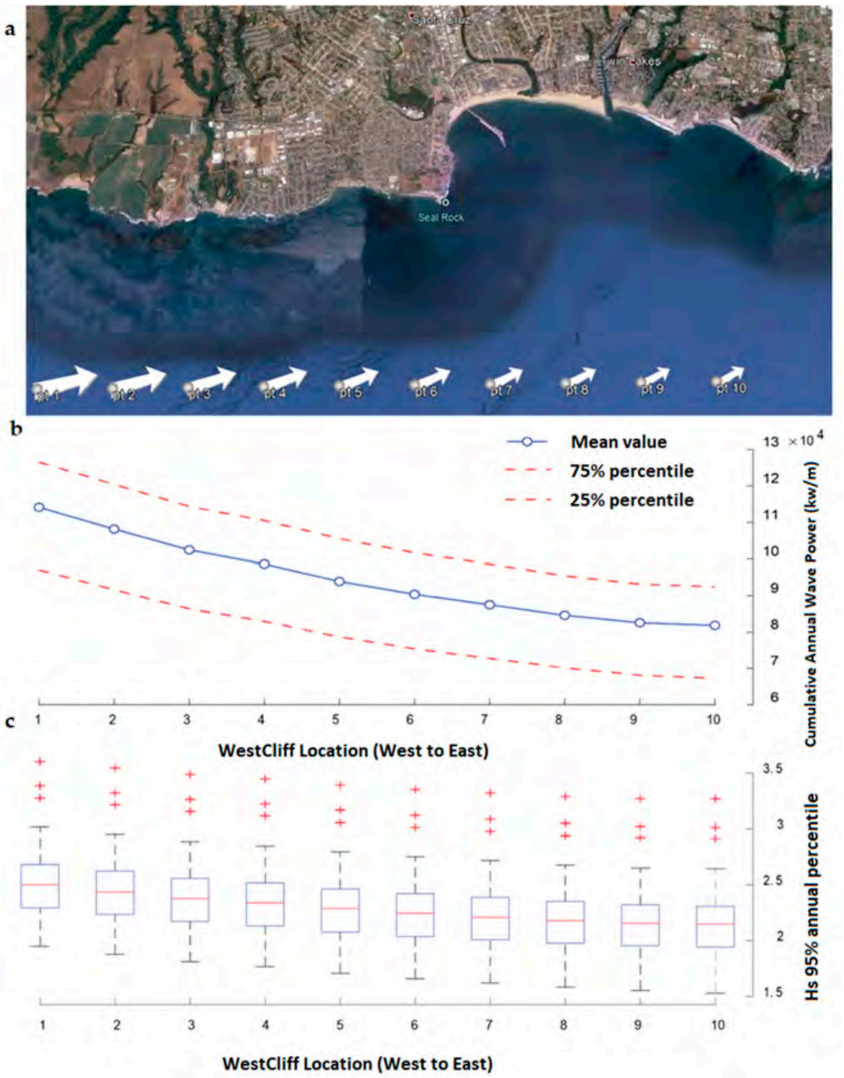

Figure 9. Spatial variation of wave climate along West Cliff. (**a**) Locations of data points with time series of wave parameters and mean direction and intensity of annual Wave Power. (**b**) Eastward variation of cumulative annual wave power. (**c**) Eastward variation of the 95% percentile of significant wave heights (Hs). The boxes represent the range between the 20% to 75% values, where the mean is indicated in red. The crosses represent values exceeding that range.

3. Materials and Methods

In this research we used both qualitative and quantitative assessments to analyze coastal cliff and bluff retreat along the West Cliff Drive coast as a case study to identify the challenges of determining historical erosion rates.

3.1. *Qualitative Coastline Change Assessment*

We conducted a qualitative assessment by reviewing literature and relevant documents on California coastline erosion, in addition to investigating the geological history, cliff geomorphic differences, sea-level rise, and related impacts on coastal erosion and history of coastline changes throughout the study area.

3.2. Quantitative Coastline Change Analysis

- Materials

We selected two historical sets of aerial photograph from 1953 and 1975 (scale = 1:10,000), and satellite imagery (Google Earth) from 2018 (Figure 10). This gave us a significant span of time to achieve useful results for extracting coastlines and comparing them to detect coastline change, identifying cliff and bluff retreat, as well as measuring the erosion rates along this coast. We also used a hill-shaded digital surface model (USGS, 2018), as well as historical ground and modern photos of the area to digitize and adjust the selected reference line in each segment as accurately as possible. GIS tools were used to perform coastline change detection.

Figure 10. Aerial photographs (**a**) 1953, (**b**) 1975, and (**c**) satellite imagery (2018).

- Methods

Cliff and bluff retreat were analyzed through three main stages:

1. Defining the reference coastline: For digitizing the coastlines and being able to compare them in order to measure coastal retreat, we defined the reference lines that were detectable on both the aerial photographs and satellite imagery and that also could represent the cliff or bluff retreat over the studied time span. Due to the diverse cliff and bluff profiles (Figure 11), three different lines were defined and extracted from the vertical images: a. Cliff/bluff edge; b. the base of bluff; and c. the base of cliff (Figure 12). Depending on data resolution and along different segments of the coast, we selected the line that was the clearest and most detectable for extraction on both the aerial photographs and satellite imagery to use in the analysis.
2. Geometric correction and extracting reference lines: In order to georeference the aerial photographs and perform the nonsystematic geometric correction to reduce the distortion of both the aerial and satellite imagery, we used 19 ground control points (GCPs) that were identified on the two historical aerial photographs and the satellite imagery and collected their coordinates during a field survey. To remove the spatial error (coastline positioning error) as much as possible, we also performed a geometric correction on 31 different coastal segments (Figure 13) using common features which were distinguishable on both aerial photographs and satellite imagery. We then digitized the identified reference line of each segment independently.
3. Coastline change assessment: Analyzing extracted coastlines position led us to historical cliff or bluff retreat rate measurements along West Cliff Drive and allowed us to evaluate the challenges of widely used methods in coastline change studies.

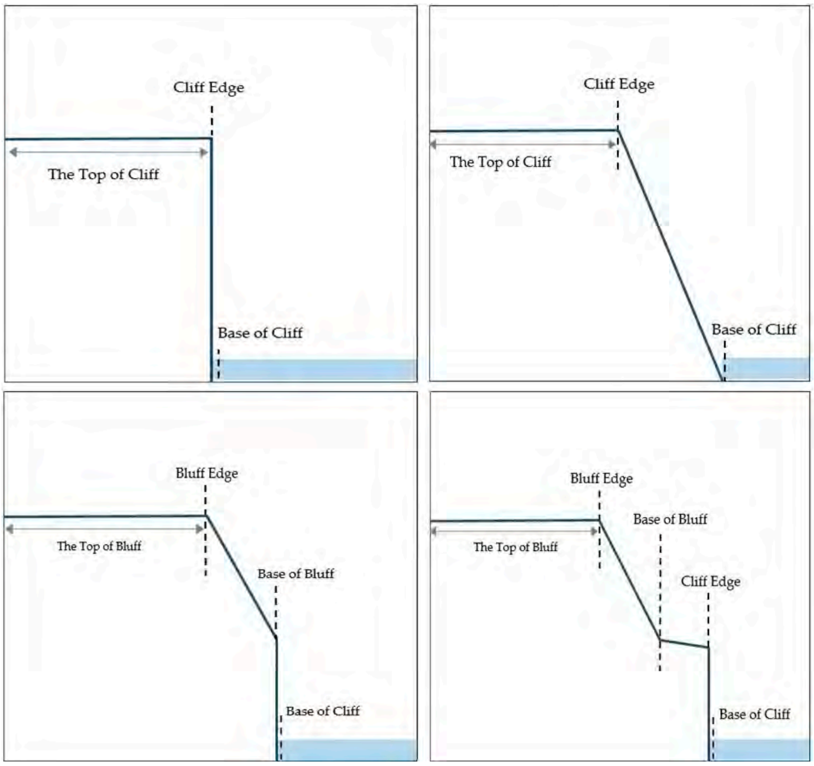

Figure 11. The various profiles and related reference lines (coastline) along cliffed coasts.

Figure 12. The defined reference lines along a cliffed coast. (**a**,**b**) profile view (**c**) vertical view. (In this segment of coast, the detectable reference line on both aerial photographs and satellite imagery was "the base of bluff").

Figure 13. Map of the 31 identified coastal segments, armored coastline, and unprotected areas along the West Cliff Drive coast—(**a**) West side (**b**) East side.

4. Results

4.1. *Qualitative Coastline Change Assessment*

- Geology

Erosion along the West Cliff Drive coastline typically occurs through a combination of wave impact, weathering and abrasion of the bedrock, rainfall and terrestrial runoff to a lesser degree, and also relatively infrequent seismic shaking during large earthquakes. Bedrock erosion along weaker stratigraphic layers or joint sets leads to focused erosion and the frequent formation of undercuts, arches, caves, and embayments that made this area an early attraction for residents and visitors. The Santa Cruz Mudstone is more resistant to wave attack than the Purisima Formation and retreats at slower rates overall. As described above, it is primarily the well-developed joint in the latter formation that focuses erosion and typically leads to the failure of large joint-bounded blocks or the collapse of arches and caves. The unconsolidated sandy terrace deposits are much less resistant to wave attack, and it is during periods of large storm waves coincident with very high tides that waves overtop the bedrock and attack and erode the weaker terrace deposits. It is this erosion that has historically threatened and undermined sidewalks, West Cliff Drive, and also a historic lighthouse. Coastal erosion or cliff and bluff retreat in the study area, as along most of the California coast, is an episodic process with most of the major cliff failures occurring during the simultaneous arrival of large storm waves and elevated sea levels.

- Coastal Protection and Erosion

Efforts to stabilize or protect this stretch of shoreline from wave erosion began in 1926 and have continued intermittently to the present. Concrete retaining walls along the upper bluff and rip-rap revetments at the base of the cliff have been the dominant type of armor emplaced, although broken slabs of old streets and sidewalks and stacked bags of concrete were also used in the early years in attempts to halt or slow cliff retreat. Today of the 5800 m of coastline studied, about 2600 m or 44.8% has been armored (Figure 13), with 91% of this armor consisting of rock revetments (Figure 14). While this has served to reduce and halt erosion, it has completely changed the natural condition and appearance of this stretch of coast. These large revetments have also covered large areas of sandy beach that are now removed from public use. The local government agency (City of Santa Cruz Department of Public Works) received emergency permits to install much of the rip-rap, but some of these permits were never finalized with the permitting agency (California Coastal Commission). The Coastal Commission has recently required that the city evaluate the coastal erosion and protection issues, public use, and economics of this 5800 m stretch of coastline and develop a long-term management plan for the future.

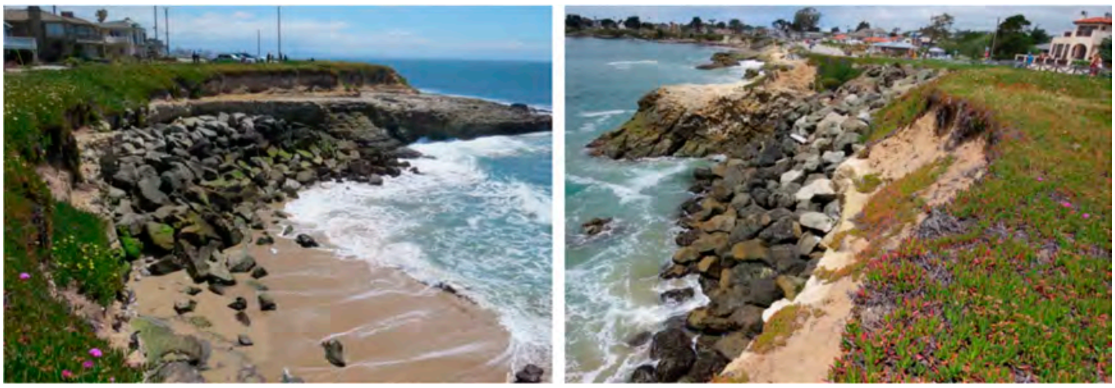

Figure 14. The placement of rip-rap over a 60 year period has reduced or eliminated bluff retreat along about 50% of West Cliff Drive, thus complicating any measurements of natural rates of bluff retreat.

- Coastal Change from Historical Ground Photographs

As soon as cameras became widely available, residents, visitors, and commercial photographers began to take pictures of the Santa Cruz coastline. The earliest dated photographs we have discovered of this coast were taken 143 years ago (1876). Certain areas, the picturesque arches, sea stacks, and distinct rock formations along West Cliff Drive, for example, were photographed frequently and memorialized in hand-colored postcards and family albums. Over the subsequent years, as winter storms have periodically battered the bluffs and beaches, and sea level has gradually risen, the coastline has slowly retreated. Some areas have changed dramatically (Figures 15a–c and 16a,b), and others have changed surprisingly little. The natural bridges, arches, and sea stacks that owe their origins to wave attack of the weaker sandstones and mudstones have been destroyed by the same forces that created them, with many fascinating and revealing photographs taken of these natural and unnatural features along the way. While it is very difficult to get any quantitative measurements of cliff or bluff retreat from old ground photographs, they do provide a clear record of the extent of change or retreat that has taken place since the time the original photograph was taken. In many cases, and for most people, a then and now set of photographs provides a more understandable record of coastal change than a rate of retreat in cm/year [48].

Figure 15. (**a**–**c**) Progressive erosion of an arch in the study area over a period of 50 years to ultimately form a sea-stack. Dates of photos: (**a**) Before 1888, (**b**) ~1890, (**c**) 2005.

Figure 16. (**a**–**c**) Promontory in foreground and Bird Rock arch (in background) in 1909, 2005, and 2019.

4.2. Quantitative Coastline Change Assessment

- Documenting Coastal Erosion from Vertical Aerial Photographs and Maps

The first aerial photographs were taken of the Santa Cruz coast in 1928 and were in stereo. This is quite amazing as Charles Lindberg had just made the first solo flight across the Atlantic Ocean the year before. These photographs were taken in order to study the route of a potential highway between San Francisco and Santa Cruz and aerial photographs were the easiest way to accomplish that. These images provide us with a photographic record extending back 90 years and can be used to determine qualitative changes; because of the only moderate resolution and lack of features from which to take measurements from, they are of limited value in quantitative assessment of historic cliff erosion. Vertical stereo photos were then taken in subsequent years along the Santa Cruz coast, which became quite regular beginning in the 1940s and extending to the present. Aerial photographs were taken more often in later years as various state and federal agencies became interested in documenting the landscape including forest cover, agriculture land use, coastal conditions, and development, highway and railway routes, among other purposes. Until relatively recently, historical aerial photographs were the most common sources for documenting or measuring rates of coastal change such as coastal bluff and cliff retreat. This required first determining the scale of the photograph, and then finding locations where the position of the cliff edge could be measured from some fixed feature (a road, building, etc.) over time. There are multiple challenges involved in this approach, including: a. The scale and resolution of the aerial photographs; b. the sharpness or ease of recognition of the cliff edge; c. the presence of vegetation obscuring the cliff edge making measurements difficult or unreliable; d. the lack of a reference point on older photographs to measure from; and e. the time period covered by the photographs.

The older aerial photographs are usually not of as high resolution as recent photos and useful reference features present in more recent images may well not have existed at the time the older photographs were taken. Even though we have aerial photographs that extend back 90 years for the Santa Cruz coast, using conventional methods (such as an optical comparator or loupe, for example) for measurement is hindered by photograph resolution and appropriate features from which to take repeated measurements.

- Documenting Coastal Erosion from Satellite Imagery and DEMs

In recent decades, the availability of satellite imagery (Google Earth, for example) and Lidar (Light Detection and Ranging) derived DEMs also provided high-resolution data sets for documenting coastal cliff or bluff erosion. With the inclusion of a series of historical satellite photographs in Google Earth, adjusted to precisely the same scale on the website, typically extending back into the early 1990s, or in some cases back to the 1980s, and a built-in measuring tool, a user can determine the distance from some landmark or feature to the cliff edge relatively easy on multiple images all of the same scale. The same issues that can affect the reliability of cliff erosion measurements from historic hard copy aerial photographs still exist, however, a landmark or feature that can be recognized on all images, the resolution and scale of the images, and the clarity or ease of recognizing the cliff edge. In addition, and this is an issue along the section of Santa Cruz coast covered in this study, there are many coastal bluffs and cliffs where the feature designated as the bluff or cliff edge is somewhat subjective because of the varying geomorphology, which is related to the differences in geologic materials (Figures 6 and 17). This makes determining erosion rates difficult.

Figure 17. A section of coastal bluff consisting of the overlying weaker terrace deposits that are mostly vegetated, and the underlying Santa Cruz Mudstone that is being undercut. As in Figure 6, selecting the edge of the bluff for comparative measurements is difficult and somewhat subjective.

In addition, applying the DEMs, as well as topographic maps to extract the indicator lines such as the cliff edge are other approaches to conduct coastal change analysis. The lack of high-resolution elevation data, and the differences in resolution, and scale of available elevation data, are the main constraints to conducting a time-series analysis over a relatively long-period study and would increase the uncertainties of cliff retreat rate retreat estimations.

Further complicating the measurement of changes in cliff or bluff edges is the armoring of this coast, which has gone on for about 60 years (Figures 13 and 14), and depending upon when the rip-rap was placed, this essentially brings erosion to a near halt for a number of years. As of 2019, approximately 45% of the entire West Cliff Drive area had been armored.

- Documenting Coastal Erosion along West Cliff Drive as a Case Study

In addition to investigating the evolution of coastline change over time, we used both aerial photographs and satellite imagery, as well as the hill-shaded DSM (USGS, 2018) to assess coastline retreat along West Cliff Drive coast. The coastline was divided into 31 individual segments that were evaluated independently (Figure 18). The results (Table 1 and Figures 19 and 20) showed the maximum coastline retreat over the studied time span occurred in coastal segment number 16 (Figure 21), where the retreat rate over 65 years ranged from 0.3 to 32 m (Figure 19), and the maximum retreat rate was 0.5 m/year. (Figure 20).

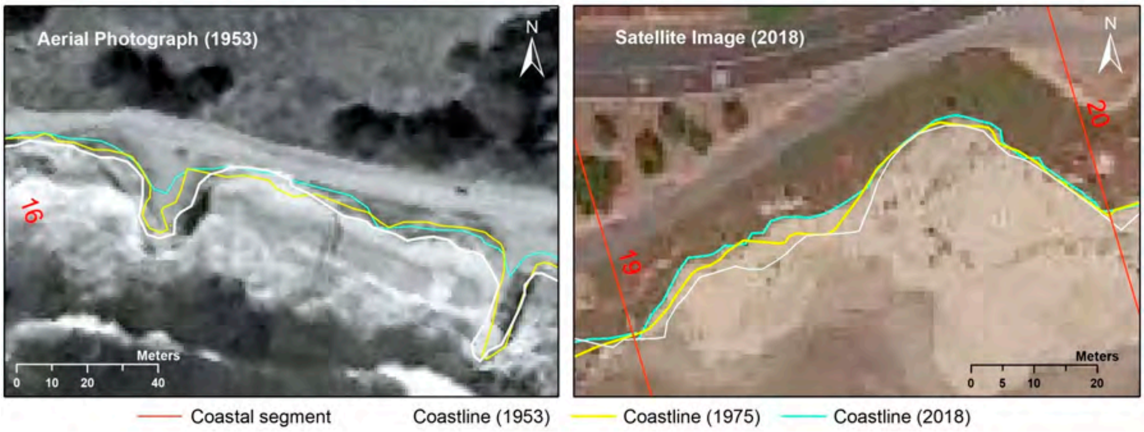

Figure 18. Two examples of digitized coastlines in segments 16 and 19.

Table 1. Coastline retreat along the West Cliff Drive Coast.

	Time span		
	1953–1975	**1975–2018**	**1953–2018**
The range of coastline retreat (m)	~0.3–19	~0.3–28	~0.3–32
The maximum retreat rate (m/year.)	~0.9	~0.6	~0.5

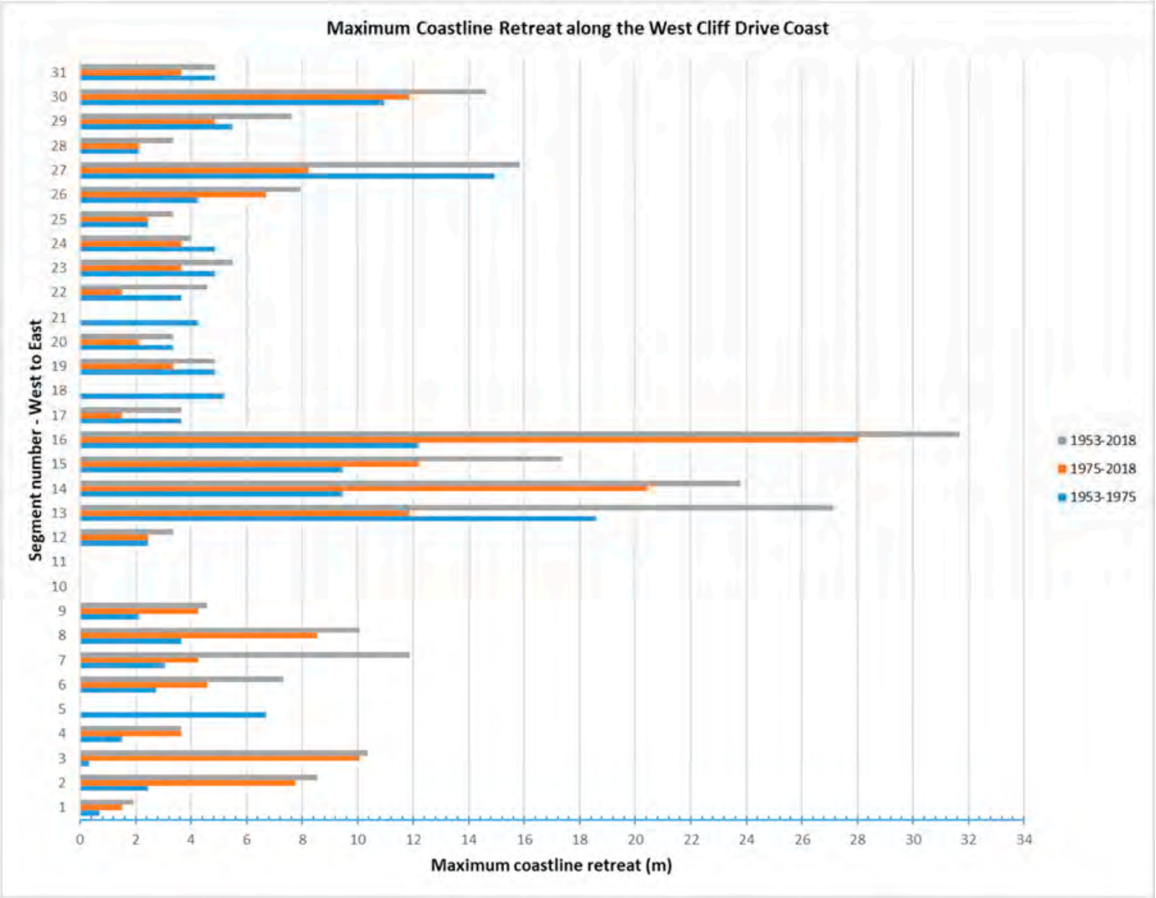

Figure 19. Maximum coastline retreat along the 31 coastal segments (zero value indicates that the change of the segment was undetectable).

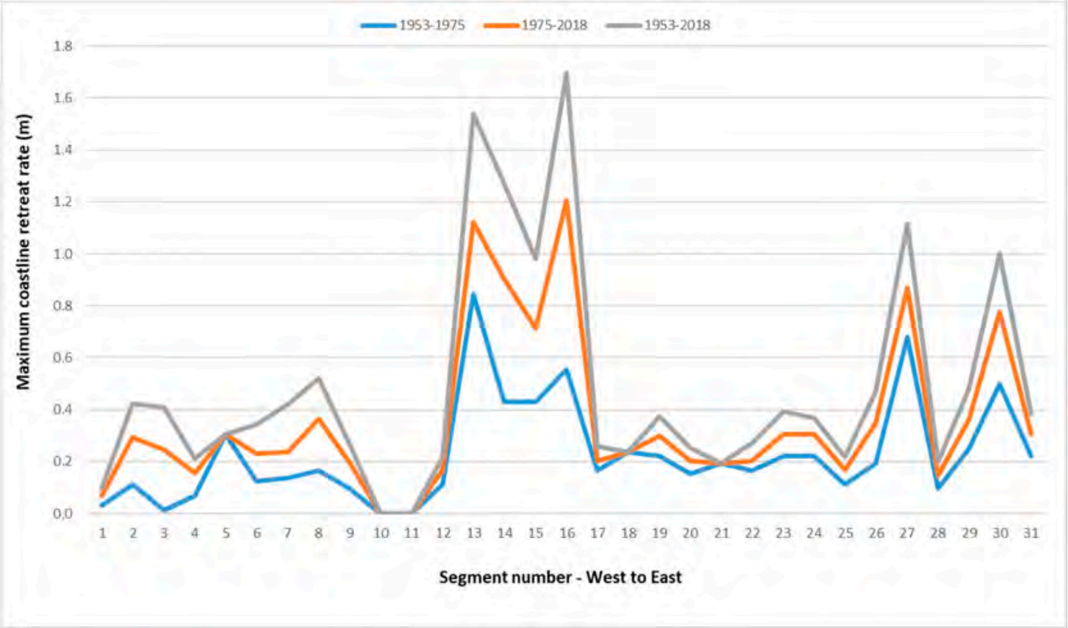

Figure 20. Maximum coastline retreat rate along the 31 coastal segments (zero value shows the coastline of the segment was undetectable).

Figure 21. Oblique aerial photographs from coastal segment number 16 (**a**) 1972 [15], (**b**) 2018 [USGS,2018].

- A Review of Cliffed Coast Retreat Studies

A number of coastal researchers have endeavored to document historical coastal cliff retreat and project future retreat along the coast of California including the Santa Cruz coastline over the years from aerial photographs, satellite imagery, and DEM, with all of the inherent challenges involved. Hapke and Reid [37] completed the most comprehensive assessment. They evaluated cliff retreat using map and photographic data for more than 350 km of the California coast over a period of approximately 70 years, as part of the US Geological Survey's Assessment of Coastal Change Program. They compared one historical cliff edge digitized from old maps dating from 1920–1930, with a recent cliff edge interpreted from LIDAR topographic surveys from either 1998 or 2002. Long-term (~70 year) rates of the retreat were calculated using differences in the locations of the two different cliff edges. The average rate of coastal cliff retreat over this time period for the sections of California coast studied was 0.3 +/− 0.2 m/year. The average amount of total cliff retreat over the 70 year period was 17.7 m. Due to the regional scale of the area studied, however, the shoreline projections were not always accurate, which affected the erosion rate determinations in specific areas. The book "Living with the Changing California Coast" [1], includes cliff and bluff erosion rates where they were published or available for a number of locations along the state's coast. Moore et al. [49] utilized aerial photos corrected through softcopy photogrammetry for a detailed study of cliff erosion rates for both Santa Cruz and San Diego counties as part of a national FEMA (Federal Emergency Management Agency) assessment of coastal erosion hazards. Unfortunately, that study did not include the West Cliff Drive area. Griggs and Johnson [50] reported on cliff erosion rates along the Santa Cruz County coastline, including a few measurements along West Cliff. Their rates were based on comparative measurements from aerial photographs taken in 1940 and 1960, but were limited by the photograph issues discussed above. Young et al. [51] detected 30 individual cliff edge failures and maximum landward retreats from 0.8 to 10 m along the 7.1 km of unprotected coastal cliffs near Point Loma in San Diego over a 5.5-year period (2003–2009). In a recently published study, decadal-scale coastal cliff retreat in southern and central California [52], cliff erosion was detected along 44% of the 595 km of shoreline evaluated, while the remaining cliffs were relatively stable.

Revell et al. [53] evaluated potential future erosion hazards along the coast of California by 2100 under a 1.4 m sea-level rise scenario. For cliff-backed shorelines future potential erosion is projected to average 33 m, with a maximum potential erosion distance of up to 400 m. Young et al. [54] studied cliff and shoreline retreat considering sea-level rise in southern California, and based on their model's results, mean and maximum scenario cliff retreat over 100 years ranged from 4–87 and 21–179 m, respectively. Barnard et al. in a study on coastal vulnerability [16], demonstrated that El Niño events result in wave directional shifts, elevated wave energy, and severe coastal erosion for the Central Pacific and California. Limber et al. [29] applied a multimodel ensemble to project time-averaged sea cliff position of the 475 km long coastline of Southern California over multidecadal time scales and large (> 50 km) spatial scales. Results showed that future retreat rates could increase relative to mean historical rates by more than twofold for the higher SLR scenarios, causing an average total land loss of 19–41 m by 2100.

5. Discussion

One of the most important types of information needed prior to initiating or approving coastal human and natural communities' protection plans, as well as any development along the coast, whether private or public, are the long-term rate at which the cliffs or bluffs are eroding. The longer the period of record covered by the aerial photographs or other data sources, the more representative will be the erosion rate calculated. Additionally, in recent decades, the challenges of a continuing rise in sea level at an accelerated rate, and changes in wave climate, which will affect the long-term cliff erosion or retreat rates, have increased the demand for historical erosion rate data that can be used to project future cliff and bluff positions in highly developed areas. Knowing where the edge of the coastal bluff or cliff is likely to be over time is important for future planning. However, most coastal change studies conclude that there are always different levels of uncertainty in erosion rate measurements and coastline retreat projection results. In this study, some of the identified challenges that could increase the result uncertainties were:

(a) Extracting a constant and continuous coastline on both the aerial photographs and satellite imagery. The combination of a complex cliffed coast profile (Figure 22), as well as diverse geology, led to several lines which could be considered as the erosion (cliff retreat) indicator. We extracted the line that was the most detectable on 31 individual studied coastal segments independently.

(b) In some areas the existing armor, as well as vegetation coverage made it impossible to extract the coastline retreat indicator, the cliff edge, for example.

(c) The low-resolution of historical aerial photographs made it difficult to recognize and extract the identified indicator line along several coastal segments.

d) Considering the data availability, we employed a nonsystematic geometric correction, however it did not completely remove the geometric errors along the coastal segments and, as a result, we did not measure the retreat of such areas.

(e) There were two other types of coastal erosion that were not detectable on vertical aerial and satellite images including undercuts and sea caves (Figure 23).

(f) The scale of the study could directly affect the accuracy of coastline change analysis. In this study, examining quantitative coastline retreat along a relatively short section of coast enabled us to use the ground photographs of the study area to adjust the modern coastline we had extracted from satellite imagery.

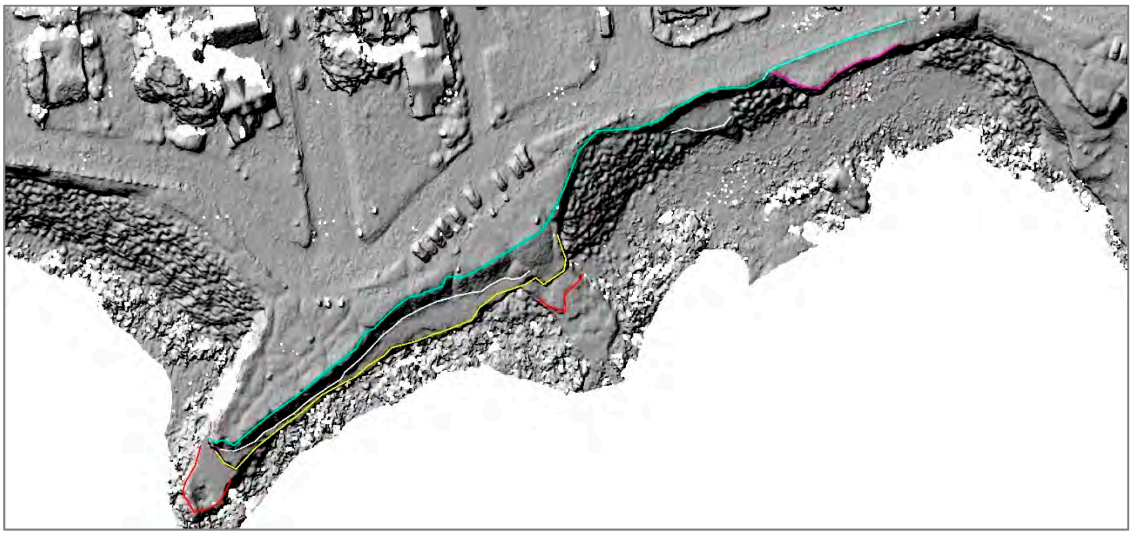

Figure 22. A hill-shaded Digital Surface Model—DSM (USGS-2018) shows the complex profile of cliffed coasts, as well as various lines which could be used in cliff and bluff retreat analysis.

Appropriately addressing the identified challenges in coastal cliff erosion studies (both qualitative and quantitative assessments) could reduce the uncertainty of the historical erosion rate measurements (cliff or bluff retreat) and, as a result, would improve the future bluff or cliff retreat projections. Erosion models include substantial uncertainty, not only derived from the definition of future sea levels and waves but also from the estimates of historical coastline retreat rates. Cliff erosion brings even more complexity and uncertainty given the interaction of the coastal geology with sea levels and waves, which produce different coastal sections with collapsing and eroding modes. Therefore, coastline change models should be contrasted with historical rates from remote sensing and historical imagery as a ground truth and expected erosion potential. While this approach may not provide quantitative definition of the future coastline, it is adequate to identify the historical impacts, delineate erosion hotspots, and establish priorities for management, today and in the foreseeable future, both from regular oceanographic conditions and episodic cycles such as El Niño.

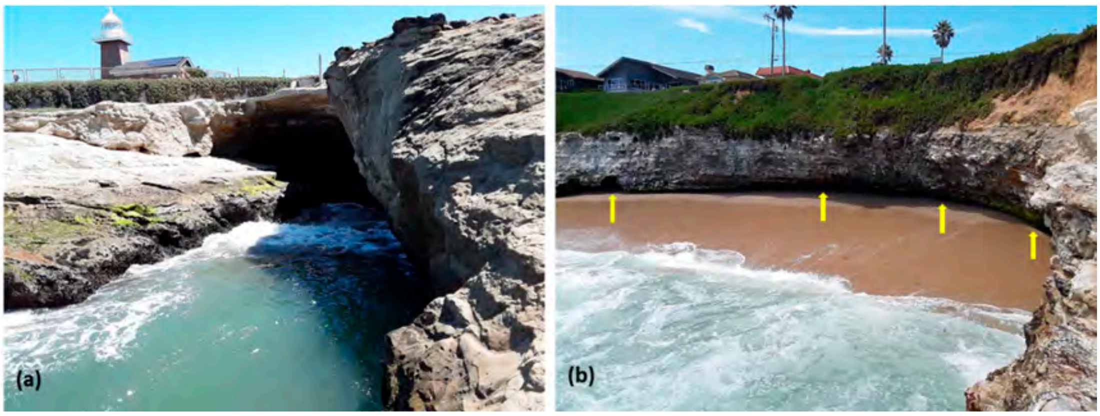

Figure 23. Seacave (**a**) and undercuts (**b**) along West Cliff Drive.

6. Conclusions

As sea level continues to rise at an accelerated rate, the intensive development and infrastructure along California's coastline is under an increasing threat. Whether construction on coastal bluffs or cliffs, or along low-lying shoreline areas, higher sea levels combined with storm waves and high tides will lead to increased rates of cliff and bluff retreat and more frequent coastal flooding. Planning and adapting to a new but uncertain coastline position is and will continue to be a major challenge for many coastal communities. However, there are challenges and uncertainties in both accurately documenting historic cliff and bluff retreat and in projecting these values into the future. There are significant obstacles for developing and implementing future sea-level rise adaptation strategies, managed retreat for example, along the coast, in particular cliffed coastal regions. Reducing or avoiding the problems and concerns identified in this study in determining erosion rates as much as possible through using the most reliable data sets and applying appropriate approaches is an essential process in developing a roadmap for the future management of the area.

Coastal cliff retreat is the product of a complex interaction between the (1) intrinsic properties of the cliff or bluff materials (lithology or rock type, internal rock weaknesses such as joint patterns, and stratigraphic variations, for example) that combine to resist erosion, and (2) the extrinsic processes (rock weathering, rainfall, wave energy, tidal range, storm frequency and intensity, and sea-level rise, for example) that work to weaken the cliff materials and produce failure or erosion. While the historic coastline data from ground and aerial photographs, maps, and satellite imagery can be used with caution and experience to provide the most accurate measurements possible of past changes, with the increase in sea-level rise rates and other aspects of climate change, conditions are shifting. Implementing a detailed coastal monitoring program to document and track the present location and condition of cliff and bluff edges, delineating armored and unarmored sections of coastline, documenting rates of sea level change, and identifying erosion hazard zones will, over time, provide a more robust foundation for future decision making.

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