

Low-Cost Drone-Based Monitoring of Coastal Erosion in California

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Abstract

Coastal erosion threatens infrastructure and communities along the California coast. This paper examines how the amount and location of coastal cliff erosion changed across survey periods along approximately 13 km of the Big Sur coastline using 27 publicly available USGS M3C2 point-cloud datasets covering 2017 to 2023. These data were created from photographs taken with a plane-mounted camera rather than a low-cost drone; however, as part of this project, a Crazyflie drone equipped with an AI Deck was built from scratch and configured for autonomous flight as a prototype for future coastal-monitoring studies. A workflow was created to inspect the clouds, create representative samples, measure statistically significant surface change, and divide the coastline into 250 m segments. The largest sampled 95th-percentile erosion distance was 4.161 m for the period from March to July 2020, while 82.54% to 100% of points were classified as significant change depending on the survey interval. The analysis also identified 62 candidate erosion hotspot cases across different coastal segments and time periods, demonstrating that both erosion magnitude and hotspot location varied considerably between surveys. These results show that repeated cloud surveys can reveal important spatial and temporal patterns in coastal erosion and provide a practical baseline for evaluating whether low-cost autonomous drones can produce accurate and affordable coastal-monitoring data. View the project repository at github.com/PeskyPenguin13/Big-Sur-coastal-erosion-analysis.

Introduction

Coastal erosion is the gradual loss or movement of land along a coastline due to processes such as waves, storms, currents, and changes in sediment supply. Although coastlines naturally change over time, erosion can become a serious problem when beaches and coastal cliffs retreat toward homes, roads, and other infrastructure. California is particularly interesting for studying coastal erosion because of its long coastline and the large number of communities located close to the ocean. Previous studies have found substantial erosion along the California coast. For example, Hapke et al. found that approximately 40% of California beaches were eroding over long time scales, while 66% were eroding over the shorter period examined in their study [3].

One difficulty in studying coastal erosion is that the coastline must be measured repeatedly over long periods of time. Traditional field surveys can be expensive and difficult, especially along cliffs or other inaccessible regions. Remote sensing provides another way to study these changes. Satellite and aerial images can be compared across different years to measure changes in shoreline position. More recently, Structure-from-Motion (SfM) photogrammetry has made it possible to reconstruct three-dimensional surfaces from a series of overlapping photographs [5]. This method is especially useful for drones because relatively inexpensive RGB cameras can be used to collect the photographs needed to create detailed three-dimensional models.

Large public datasets make it possible to study these methods without having to collect decades of new observations. The U.S. Geological Survey has published a dataset containing annual shoreline positions for 329 beach segments along California between 1984 and 2024 [4]. This dataset

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can be used to study how different sections of the California coastline have widened or narrowed over approximately four decades. In addition, the USGS has collected repeated aerial photographs of approximately 13 km of the Big Sur coastline. These photographs were processed using SfM photogrammetry to produce three-dimensional point clouds for 33 flights between 2017 and 2023 [2]. Differences between these point clouds can be used to identify locations where material has been lost from coastal cliffs.

In this paper, these datasets are used to investigate how aerial imaging and GIS techniques can be used to monitor coastal erosion in California. Particular attention is given to whether the type of imagery that can be collected using a relatively low-cost drone could provide useful measurements of coastal change. By combining long-term shoreline data with high-resolution three-dimensional coastal measurements, I explore both the large-scale patterns of coastal erosion and the possibility of using drone-based photogrammetry as a lower-cost method for monitoring areas that may be changing rapidly.

Methods

A CrazyFile 2.1+ Drone that had a Flow Deck was used for these experiments. The Flow Deck measured horizontal motion and height above the floor. The tests were performed inside, on a clear, flat surface with no interference. Two maneuvers were tested: hovering at a fixed position and following a circular path.

Hover Control

While vertical flight, the forces acting upon the drone were upward motor thrust T and the downward gravitational force mg . The vertical dynamics were modeled as:

$$m\ddot{z} = T - mg, \quad (1)$$

which gives:

$$\ddot{z} = \frac{T}{m} - g. \quad (2)$$

For a stationary hover, the acceleration has to be zero, so the thrust must balance and be equal to the weight

$$T = mg. \quad (3)$$

The vertical position error was defined as:

$$e = z - z_0, \quad (4)$$

where z is the measured height and z_0 is the desired height. Therefore, $e > 0$ indicates that the vehicle is above the target, while $e < 0$ indicates that it is below the target.

The thrust command was adjusted using position and velocity feedback:

$$T = mg - k_p(z - z_0) - k_v\dot{z}, \quad (5)$$

where k_p is the gain in position and k_v is the velocity gain. Substitution into the vertical dynamic gives:

$$\ddot{z} = -\frac{k_p}{m}(z - z_0) - \frac{k_v}{m}\dot{z}. \quad (6)$$

The Drone took off, moved to the desired height, hovered at the commanded position, and then landed.

Circular Flight

For the circular-flight test, the desired horizontal position was formed using

$$x_d(\theta) = x_c + r \cos(\theta), \quad (7)$$

$$y_d(\theta) = y_c + r \sin(\theta), \quad (8)$$

where (x_c, y_c) is the center of the circle, r is the radius, and θ determines the position of the drone along the circular path.

The desired position can also be written using a rotation matrix:

$$\begin{bmatrix} x_d - x_c \\ y_d - y_c \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} r \\ 0 \end{bmatrix}. \quad (9)$$

The angle was increased during the experiment so that the commanded object moved around the circle. The Drone followed these position commands while also maintaining a constant height using the hover controller described in the above subsections. After completing the circular path, the vehicle returned to hovering and landing.

Results

The analysis used the USGS Big Sur dataset published by Dow et al. [1]. The dataset contained 27 M3C2 survey comparisons covering approximately 13 km of the Big Sur coast between January 2017 and June 2023. M3C2 compares two three-dimensional surface surveys and measures how far the coastal surface changed between them. Positive M3C2 distances represent erosion in this dataset. The time between the start and end surveys varied across the study. Several surveys were completed during early 2023, while other intervals covered several months. The sampled point locations and the timing of each comparison are shown in Figure 1.

Erosion magnitude

Erosion magnitude varied considerably among survey intervals (Figure 2a). The median erosion distance was generally below 0.4 m. However, the 95th percentile was much larger during some intervals, showing that a smaller number of locations experienced stronger erosion. The largest sampled 95th-percentile erosion distance was 4.161 m for the March 19–July 5, 2020 interval.

The percentage of points classified as significant change ranged from 82.54% to 100% (Figure 2b). Most intervals had values close to 100%. The lowest percentage occurred during the January 29–March 7, 2018 interval.

The combined erosion-distance distribution was strongly right-skewed (Figure 2c). Most positive erosion distances were small, but a smaller number of points had much larger values.

Spatial erosion patterns

The location of strong erosion changed among survey intervals (Figure 3). The coastline was divided into 250 m segments to compare erosion along the study area. A total of 62 segment–interval combinations met the candidate-hotspot rule. These cases had a 95th-percentile erosion distance of at least 2.088 m and contained at least 30 sampled significant erosion points.

Candidate hotspots occurred in several parts of the coastline rather than in one continuous area (Figure 3a). The heatmap also shows that erosion magnitude changed through both space and time (Figure 3b). Some segments had high erosion during only one interval, while others appeared as candidates during several intervals.

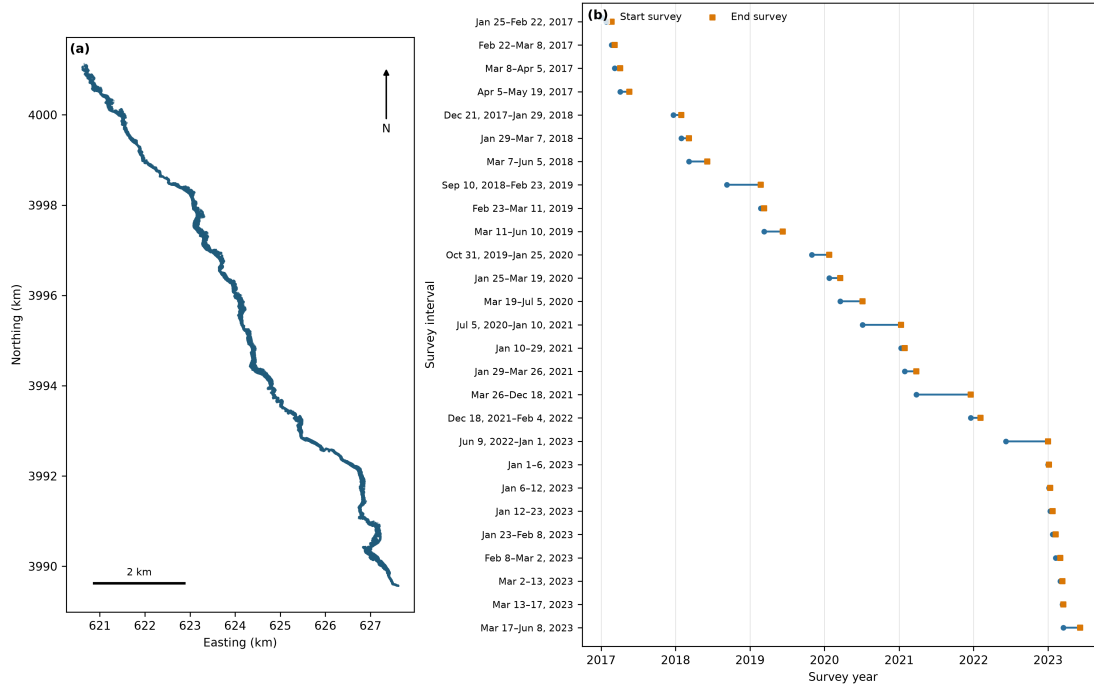


Figure 1: Spatial and temporal coverage of the dataset. Panel (a) shows where sampled M3C2 change measurements were available along approximately 13 km of the Big Sur coast. Panel (b) shows the 27 survey intervals, with each line connecting the start and end surveys.

Quality and sensitivity checks

Figure 4a compares the measured surface change with its estimated uncertainty. Uncertainty describes how precisely the change was measured; smaller values indicate greater confidence. In this dataset, positive M3C2 distances represent erosion. Negative distances mean that the surface moved in the opposite direction and may represent sediment gain, surface buildup, or measurement effects rather than erosion.

Most sampled points had low uncertainty. Every M3C2 distance was stored as a valid number, and no uncertainty values were below zero. Three points had change distances slightly greater than 20 m in either direction. These unusual values were flagged for quality control but were not removed.

The Visible Atmospherically Resistant Index (VARI) is a simple measure of surface greenness calculated from the red, green, and blue color values of each point:

$$\text{VARI} = \frac{G - R}{G + R - B},$$

where G , R , and B represent the green, red, and blue values. Positive VARI values can indicate a greener surface and may suggest vegetation, while values at or below zero generally indicate less greenness. However, VARI is only a screening measure and does not prove that a point represents vegetation.

Figure 4b compares VARI with M3C2 distance. A total of 535,915 points, or approximately 1.4% of the dataset, had VARI values greater than zero. These points were not automatically classified as vegetation because the USGS dataset had already been filtered and manually reviewed. Some positive VARI values may therefore represent real cliff surfaces, color differences, or remaining vegetation.

A sensitivity check was performed by recalculating the median erosion distance after removing

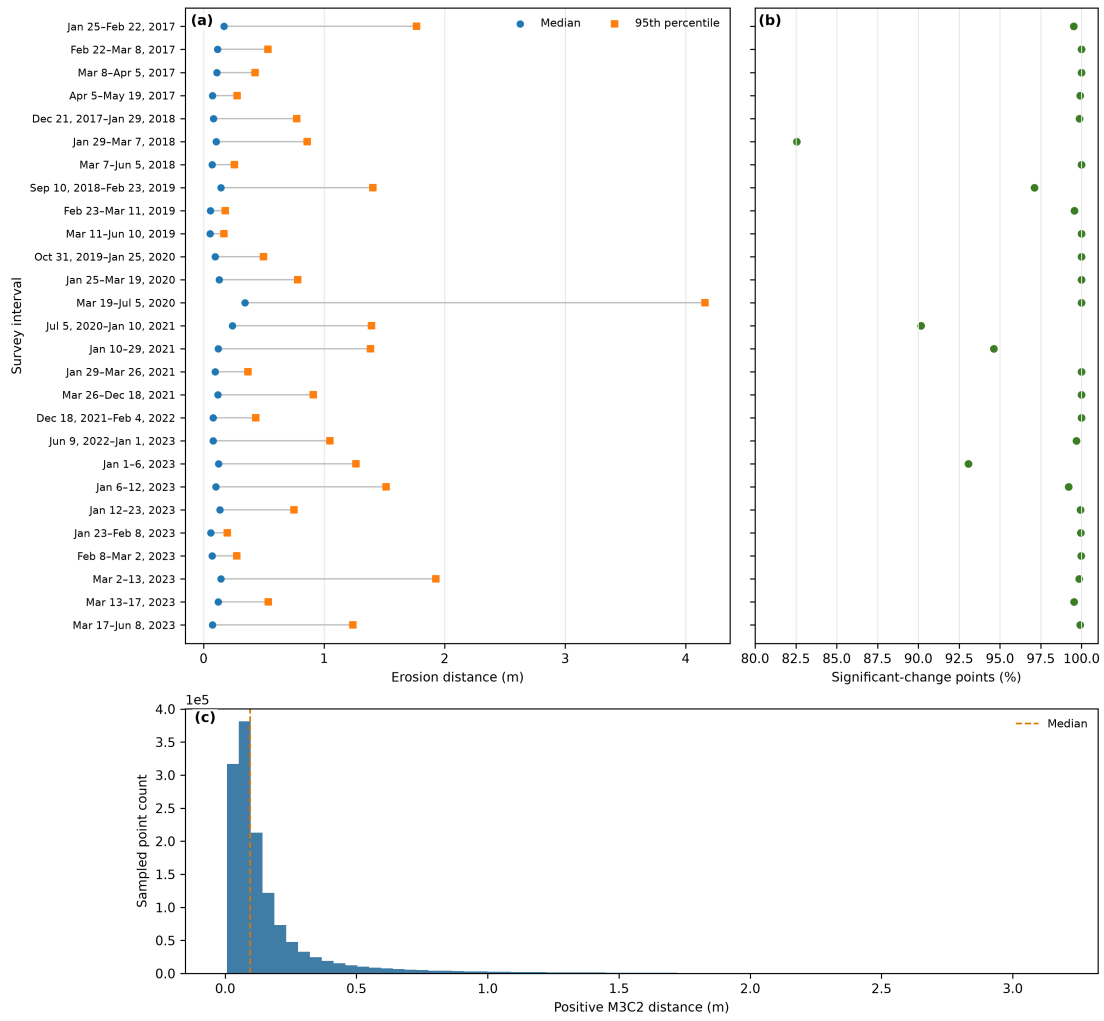


Figure 2: Erosion magnitude and significance across survey intervals. Panels show (a) median and 95th-percentile erosion distance, (b) the percentage of points classified as significant change, and (c) the distribution of positive erosion distances.

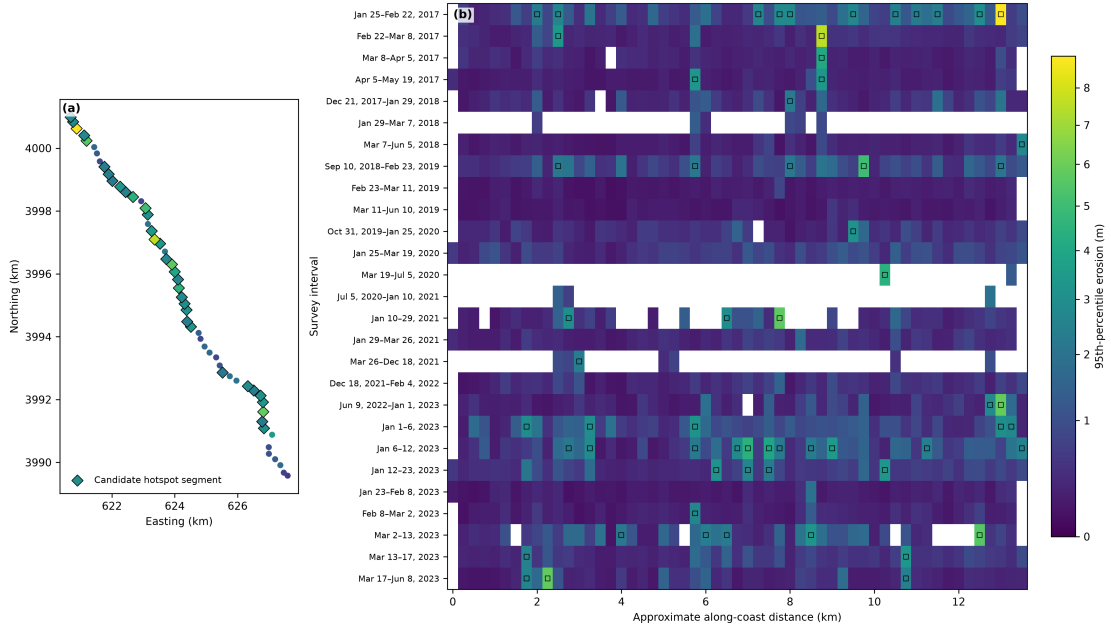


Figure 3: Spatial and temporal patterns of coastal erosion. Panel (a) shows the maximum 95th-percentile erosion for each 250 m segment. Panel (b) shows erosion magnitude by coastal segment and survey interval, with outlined cells marking candidate hotspot cases.

points with VARI greater than zero. In Figure 4c, the horizontal axis shows the median before this additional screen, and the vertical axis shows the median afterward. The dashed line represents no change between the two results. Most points are close to this line, showing that the additional VARI screen had little effect during most survey intervals, although a few intervals changed more noticeably.

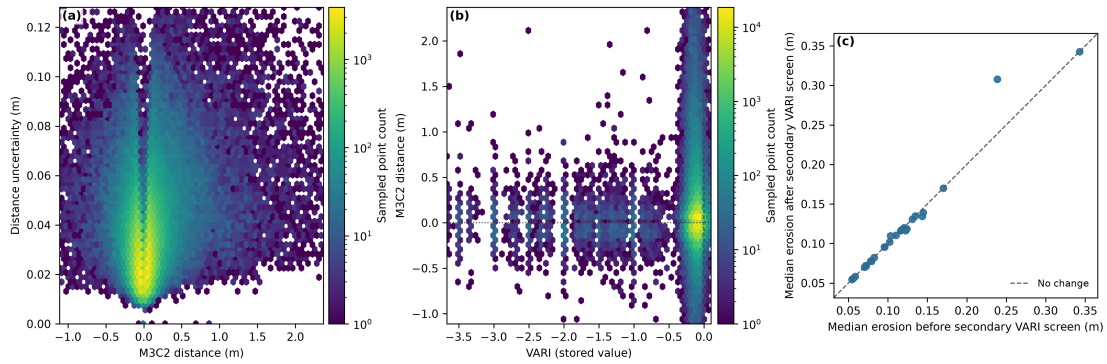


Figure 4: Data-quality and vegetation-sensitivity checks. Panels show (a) M3C2 distance and uncertainty, (b) M3C2 distance and VARI, and (c) median erosion before and after the secondary VARI screen.

The results show that coastal erosion varied strongly across both survey intervals and coastal segments. The largest changes were concentrated in a limited number of locations and time periods.

Conclusion

This paper examined coastal cliff erosion along approximately 13 km of the Big Sur coast using 27 USGS M3C2 point-cloud comparisons from 2017 to 2023. The results showed that erosion varied strongly across both time and location. The largest sampled 95th-percentile erosion distance was 4.161 m during the March 19–July 5, 2020 interval. In addition, 62 coastal segment–interval combinations were identified as candidate erosion hotspots.

Most survey intervals contained a high percentage of points classified as significant change. However, the magnitude and location of erosion were not consistent between intervals. Some coastal segments experienced strong erosion during only one period, while others appeared as candidate hotspots several times. This demonstrates the importance of repeated surveys because a single survey comparison may not represent the longer-term erosion pattern.

The quality checks found no nonfinite M3C2 distances or negative uncertainty values. The additional VARI screen produced only small changes in median erosion for most intervals. This suggests that the main erosion results were generally stable, although vegetation, point density, surface orientation, and uneven survey coverage remain possible sources of uncertainty.

The source photographs were collected using a plane-mounted camera rather than a low-cost drone. Therefore, this study does not directly demonstrate that low-cost drones can reproduce the USGS results. Instead, the analysis provides a reference for planning future drone-based coastal monitoring. Future work should collect repeated drone surveys over selected hotspot and non-hotspot segments, use independent ground-control and check points, and compare drone-derived changes with established reference data.

The repeated point-cloud surveys provide a useful way to identify when and where coastal erosion occurs. A carefully designed low-cost drone program could support more frequent monitoring of accessible coastal cliffs. However, field validation and consistent survey methods are needed before drone measurements can be used for long-term management or hazard decisions.

References

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