

Pismo Beach Sand Dynamics: A Drone Study of 2024–25 Winter Swells

Introduction

Sandy intertidal beaches hold much recreational (McLachlan et al. 2013), commercial (Seitz et al. 2014), and ecological (Wilson et al. 2005) value. However, climate change and human population growth present a variety of negative impacts on such coastal communities both locally and globally (Defeo et al. 2009); (Brown and McLachlan 2002). Since this ecosystem constitutes about half of the world's ice-free ocean coastline (Defeo et al. 2021), monitoring how these beaches respond to various threats may be critical for informing future conservation and management efforts.

Globally, sandy beaches on the coast are facing threats that include erosion (Moore, Benumof, and Griggs 1999), climate-change-induced sea level rise (Cayan et al. 2008), and continued human development (Griggs and Battalio 2024). The negative impacts of such processes are being felt by both biological and human communities along the coast. Coastal ecosystem functions are being altered enough to reduce ecosystem services such as wave protection, fisheries, and other essential services (Nelson et al. 2013) which many coastal communities are economically reliant on (Barbier et al. 2011). For example, Nelson et al. (2013) highlight how undeveloped coastal habitats like wetlands and dunes, which naturally protect against storm surge and flooding, are becoming increasingly valuable as rising sea levels and stronger storms put more coastal populations and infrastructure at risk. However, undeveloped coastal habitats like wetlands and dunes are themselves increasingly threatened by coastal development, recreational overuse, invasive species, and sea-level rise—all of which can undermine their ecological integrity and reduce their capacity to provide natural protection and

biodiversity support. However, management decisions, particularly on sandy beaches, often prioritize economic and cultural uses—such as tourism, coastal real estate development, and recreational activities like off-highway vehicle (OHV) use—over ecological considerations. These uses can lead to habitat degradation, erosion, and disturbance of wildlife, all of which compromise the ability of beaches to maintain key ecosystem services like shoreline stabilization, habitat for sensitive species, and natural water filtration (Laitano, Chiaradia, and Nuñez 2022; Shaw et al. 2011). This suggests an increasing need for coastal management strategies to consider more holistic approaches, given that environmental health and economic stability are intrinsically connected.

As the primary driver shaping beach morphology, sand determines elevation, slope, grain size, and substrate stability (Bozzeda et al. 2023)—all of which directly influence the ability of beaches to provide essential ecosystem services such as shoreline protection, habitat for intertidal organisms, and natural filtration. The movement, retention, and redistribution of sand—shaped by diverse forces such as seasonal wave energy, episodic storm events, and anthropogenic activities—play distinct roles in coastal dynamics. Seasonal wave energy governs regular patterns of sand accretion and erosion; for instance, low-energy summer waves typically promote onshore sand transport and beach buildup, while high-energy winter waves drive offshore movement and beach flattening (Warrick et al. 2019). Storm events, particularly intense winter swells, can rapidly erode dunes, reshape beach profiles, and alter sediment grain-size distributions, sometimes with long-lasting geomorphic consequences (Scott et al. 2016; Eidam et al. 2019). Meanwhile, anthropogenic alterations—such as beach grooming, OHV traffic, and coastal development—can disrupt sediment budgets by compacting sand, removing

organic material, and interfering with natural dune formation (Schlacher et al. 2014; Dugan and Hubbard 2010). Together, these sand dynamics dictate the physical structure of beaches—affecting slope, width, and grain size—which in turn determine the suitability of habitats for key intertidal species. Ecosystem resilience depends on this structural integrity: beaches with dynamic but recoverable sand regimes can better support biodiversity, buffer storm impacts, and sustain ecosystem services even under environmental stress (Defeo et al. 2021). Understanding these sand dynamics is therefore critical not only for geomorphological assessment but also for anticipating ecological responses and informing coastal management strategies.

Sand is deposited in and removed from coastal environments through complex processes influenced by various natural factors. Deposition occurs through mechanisms such as dune formation, river transport, and low-energy wave conditions, while removal is primarily caused by wind and high-energy waves (Angnuureng et al. 2023). In temperate environments such as California, these processes follow distinct seasonal patterns, with summer typically characterized by low wave energy and sand accretion, and winter by higher wave energy and sand removal (Warrick et al. 2019). During summer, onshore-directed transport processes related to wave asymmetry and wave-induced streaming become dominant, usually resulting in beach accretion. Conversely, winter brings higher-energy waves and more frequent storms, causing increased erosion as storm waves typically move sediments offshore (Warrick et al. 2019; Eidam, Ogston, and Nittrouer 2019).

While regular winter conditions cause some sand removal, certain winter storms can have an even more significant impact on coastal landscapes. These extreme events

can cause dramatic changes to coastlines, sometimes requiring significant recovery efforts and potentially altering the coastal environment for extended periods (Scott et al. 2016). Like other major weather events, these winter storms are growing more frequent and intense as a result of climate change (Cinto Mejía and Wetzel 2023; Iwasaki and Noda 2018).

These global pressures are especially evident along the California coast, where a combination of rising sea levels, increasing storm intensity, and extensive coastal development has placed significant stress on sandy beach systems—particularly along the more exposed and ecologically valuable Central Coast. Furthermore, the California coast is subject to highly destructive winter swell events (Young et al. 2018; Storlazzi et al. 2000). Pismo Beach (35.141300, -120.642082), located on California’s central coast, was selected as the study site due to its wide, sandy intertidal zone, ecological importance, and history of intense swell exposure. With nearly seventeen miles of uninterrupted waterfront, it spans multiple towns, contains designated space for OHV recreation, and neighbors an inland array of dunes. The beach provides habitat for a large sandy intertidal community, including the currently endangered Snowy Plover (*Charadrius nivosus*) and the Pismo Clam (*Tivela stultorum*), which supports a culturally and economically significant recreational fishery. Both species rely on the physical characteristics of sandy beaches—plovers require wide, low-slope beaches for nesting, while Pismo clams depend on fine- to medium-grained sediments for burrowing and survival (Marquardt et al. 2023a). High-energy storm swells can significantly reshape beach morphology by scouring finer sediments from the intertidal zone and depositing coarser material, leading to an overall coarsening of the beach substrate (Warrick et al. 2019; Eidam et al. 2019).

These shifts in grain size and beach profile can directly affect habitat suitability for key species. For instance, Pismo clams rely on stable, fine- to medium-grained sediments for burrowing and feeding; when storm activity increases median grain size above ~ 0.5 mm, clam densities have been shown to decline sharply (Marquardt et al. 2024). Similarly, snowy plovers require wide, low-slope beaches for nesting and brood rearing, and storm-driven erosion can temporarily narrow beaches and reduce elevation, increasing nest flooding risk and reducing viable nesting area. Thus, storm-induced sediment changes may not only alter physical beach structure but also constrain critical habitat availability for both intertidal and coastal dune species. This underscores the ecological importance of monitoring sand dynamics, not just for geomorphic insights but for managing habitat resilience for intertidal communities.

In recent years, California's central coast has experienced extreme swell events, including back-to-back high-energy winters in 2022 and 2023. In light of this regional context, the winter of 2024–2025 presented another opportunity to evaluate how such conditions affect sandy beach systems. This study tests the hypothesis that the 2024–2025 winter swell event significantly altered beach elevation and sand volume along Pismo Beach. By conducting monthly unmanned aerial vehicle (UAV)-based surveys from May 2024 to April 2025 across three study sites, I aimed to capture both seasonal changes and storm-driven impacts in beach morphology.

The central coast experienced two large swell events that coincided with king tides in December 2022 and 2023. These events greatly redistributed the sand across the beach, levelling many foredunes and pulling much of that sand into the swash zone or

further into the subtidal (Armitage et al., 2014). In order to understand the extent of such impacts, we need long-term monitoring efforts that can be conducted efficiently and cost-effectively. Historically, sand movement has been monitored using techniques such as sediment traps, which involve deploying physical containers or mesh devices to capture moving particles for later lab analysis, and shoreline videography, which requires mounting and maintaining fixed camera systems to track visible changes in beach profile over time (Amos et al. 2020). These methods, while informative, can be labor-intensive and costly due to their reliance on specialized equipment, frequent site visits for maintenance or sample collection, and post-processing of either physical samples or large volumes of image data. For example, sediment traps must often be deployed over long time periods and across multiple spatial points to generate reliable transport estimates, while video monitoring systems require calibrated installations and data storage infrastructure. These logistical demands can pose financial and operational barriers, especially for long-term or large-scale monitoring efforts.

In recent decades, drones have emerged as a cost-effective and efficient method for gathering high-resolution data on a wide range of attributes across many systems. In the context of sandy beaches, drones have been used to manage coastal zones (Kandrot, Hayes, and Holloway 2022), monitor beach erosion (Novais et al. 2023), assess beach nourishment programs (Kelaher et al. 2023), and even conduct citizen science surveys on coastlines (Pucino et al. 2021). These unmanned aerial vehicles (UAVs) equipped with various sensors, including multispectral and thermal cameras, enable researchers to conduct regular surveys, track changes in beach morphology over time, and create detailed 3-dimensional models of coastal areas at relatively low cost.

To understand how beach dynamics shift over time, I conducted monthly surveys at three sites along Pismo Beach, California. Using drone imagery and ground-based reference points, I tracked changes in beach elevation and sand volume over a 12-month period. When combined with GPS-based ground truthing data, these models allow for the calculation of month-to-month and long-term changes in 1) the relative beach elevation and 2) the relative volume of sand present.

Methods

To monitor monthly changes in beach volume and elevation, I used drone-based photogrammetry to create detailed 3D models of each study site. This approach, known as Structure from Motion (SfM), involves stitching together overlapping aerial images to reconstruct surface topography. To ensure accurate spatial scaling, each flight was paired with high-precision GPS data collected on the ground. These models allowed for quantifiable comparisons of elevation and sediment volume across time, with error estimates incorporated into each measurement.

I conducted monthly drone mapping surveys at three sites across Pismo beach, California under the approval of California State Parks. My three primary sites were located at Park Avenue (35.134549, -120.640077), Grand Avenue (35.123262, -120.634927), and Pier Avenue (35.106087, -120.631303) (Fig. 1). These are the same sites surveyed monthly by the Cal Poly Marine Conservation Lab to collect Pismo Clam (*Tivela Stultorum*) population data. On each survey, I was assisted by a California State Parks staff member who provided transportation and acted as a secondary spotter while I conducted my flights.

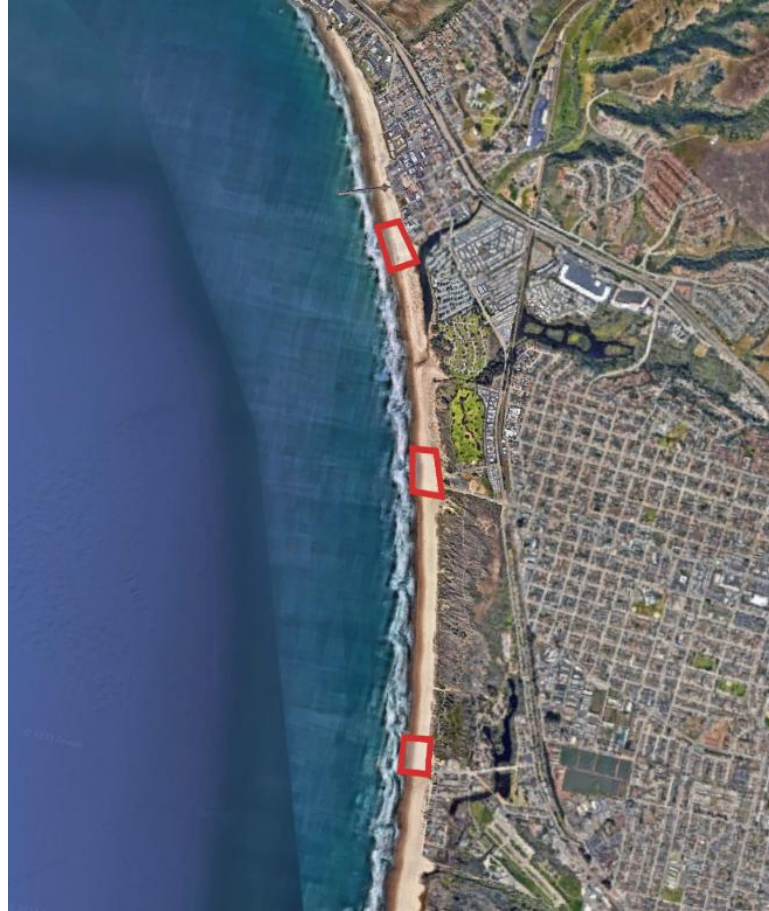


Figure 1. A map outlining the 3 study sites on Pismo Beach. From North to South, the highlighted sites are located at Park Avenue, Grand Avenue, and Pier Avenue.

These flights were conducted monthly from May 2024 to April 2025. At each site, I collected images with a Mavic 2 Pro drone. Using Pix4Dcapture, I pre-programmed a double grid flight path (Fig. 2) over each site. From the start point, the drone flew along all of the white lines then along all of the black lines until it reached the end point. Upon reaching the end point, I resumed manual control of the drone to land it, downloaded the images onto an external hard drive, and replaced the battery with a fully charged one for the next flight. For optimal SfM modeling, I set a camera angle of 70° , an overlap of 80%

between each image, and an altitude of 164 ft. above ground level (AGL). These settings were recommended by the drone mapping software for the specific quadcopter I used. After each flight, I downloaded image and spatial data from the drone's SD card. I then cleared the SD card's storage to collect data for the next flight.

Before flying at each site, I collected latitude, longitude, and elevation data using an Arrow Gold RTK at nine ground control points. These ground control points are spaced 50 feet apart, resembling a square-like shape on the ground of the area flown and are indicated by bright orange bucket lids. This was done so that when later processing the images, the specific GPS data could be linked with visually discernible points that are captured in the images.



Figure 2. An example of the double grid flight path that I pre-programmed the drone to fly.

Ground control points were placed at the 8 exterior green dots as well as one in the center.

After each monthly set of drone flights, I used Pix4Dmapper to generate a high-resolution 3D model of each study site using SfM techniques. To anchor these models

spatially, I incorporated precise ground control point (GCP) data collected using an Arrow Gold RTK GPS unit. These GCPs provided accurate latitude, longitude, and elevation references at nine fixed positions per site. Once the model was processed, I used the “compute volume” function in Pix4Dmapper to estimate the relative sand volume at each site. This function calculates the volume of material above a defined base plane by integrating the elevation values across the entire spatial footprint of the survey area. Thus, the combination of accurately georeferenced elevation data and a known surface area enabled reliable month-to-month comparisons of sand volume.

Each 3D model generated using Pix4Dmapper carries a degree of spatial and processing uncertainty, which stems from several sources throughout the UAV-SfM workflow. One key source of error is the positional accuracy of the ground control points (GCPs); although I used RTK correction to improve precision, vertical and horizontal deviations typically ranged between ± 2 and ± 5 cm, depending on factors such as satellite geometry, base station quality, and the visual clarity of GCPs in the imagery. Additional uncertainty arises during the image alignment and reconstruction phase, where factors like insufficient image texture, variable lighting, and limited overlap can affect how well the software stitches images into a coherent 3D surface. Finally, minor inaccuracies in the interpolation of elevation surfaces—particularly across uniformly sandy areas with few visual features—can lead to local distortions or smoothing. To address and incorporate these uncertainties, I relied on the model quality reports provided by Pix4Dmapper, which include root-mean-square error (RMSE) values for GCP alignment and surface accuracy. For each monthly model at every site, I reviewed these RMSE values to ensure vertical errors remained within an acceptable range, generally below 5 cm. These error

estimates were then used to interpret the results conservatively, ensuring that only changes exceeding the threshold of detection were considered meaningful in the context of beach elevation and volume dynamics.

To ensure valid comparisons of both elevation and volume across time and between sites, I anchored all surveys to consistent ground control frameworks. Each of the three sites had a fixed arrangement of nine ground control points (GCPs) that were spaced uniformly in a square-like grid and re-used for every monthly survey. These GCPs were clearly marked in the field with brightly colored bucket lids and surveyed using an Arrow Gold RTK GPS unit, providing high-precision latitude, longitude, and elevation data tied to the same base station each month. The GCP layout and dimensions were kept consistent across flights and across sites, which allowed the SfM models to reconstruct the same spatial footprint each month and maintain relative vertical accuracy. While comparisons across time within each site are the most robust, the consistent GCP referencing and uniform survey design also allow for cautious comparison between sites under the assumption of similar georeferencing accuracy. Still, small spatial mismatches or vertical datum differences may introduce some uncertainty when interpreting inter-site elevation offsets, and these are acknowledged when drawing conclusions. After I made all the calculations for each site each month, I used JMP Pro (v 17) to run one-way ANOVAs on the effect of site, month, and site*month on the mean elevation and volume.

Results

Across the 12-month survey, relative sand volume showed pronounced site-specific patterns but little month-to-month fluctuation (Fig. 3). Park Avenue consistently retained the greatest volume, averaging ~18 % more sand than Grand Avenue and ~24 %

more than Pier Avenue, and its error bars (based on a 95% confidence interval) rarely overlapped with those of the other sites. In contrast, the winter swell that peaked in January 2025 did not produce a clear, synchronous drop in volume at any site; instead, volumes stayed within one standard error of their long-term means. These visual patterns are supported by a two-way ANOVA that found a strong main effect of site on sand volume ($F = 14.5$, $p < 0.001$), while neither month ($F = 0.417$, $p = 0.934$) nor the site*month interaction were significant (Table 1). The graph and statistics indicate that spatial heterogeneity had the strongest influence on sand accretion along Pismo Beach during the study period.

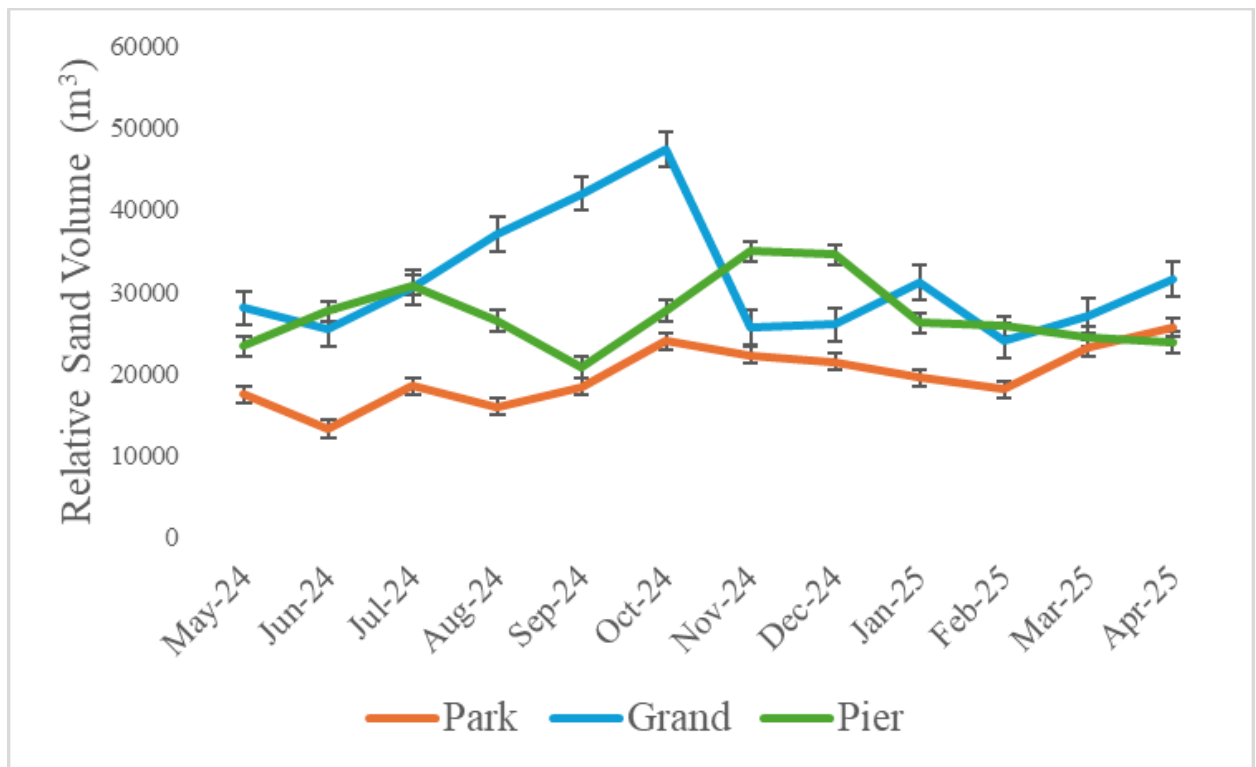


Figure 3. Monthly changes in relative sand volume at the three study sites. Error bars show mean $\pm$ 1 standard error. While overall trends were stable, Grand Avenue exhibited

a noticeable drop in sand volume from October to November, suggesting potential site-specific erosion or sediment redistribution during early winter conditions.

Mean beach elevation ASL mirrored the volume results but revealed a modest seasonal signal (Fig. 4). Elevations at Park Avenue remained the highest throughout the year, again reflecting its larger sand budget, whereas Pier Avenue tracked 10–15 cm lower for most months. Notably, all three sites dipped by 4–6 cm between December 2024 and February 2025 before rebounding by April, hinting at short-lived erosion during the peak swell. The ANOVA confirms significant effects of both site ($F = 3.88$, $p = 0.031$) and month ($F = 5.26$, $p = 0.004$) on elevation, while the non-significant site*month interaction ($F = 0.549$, $p = 0.898$) indicates that each site followed a similar seasonal trajectory (Table 1). These findings suggest that winter wave energy temporarily lowered beach surfaces across Pismo but that recovery was rapid and site rankings in elevation were preserved.

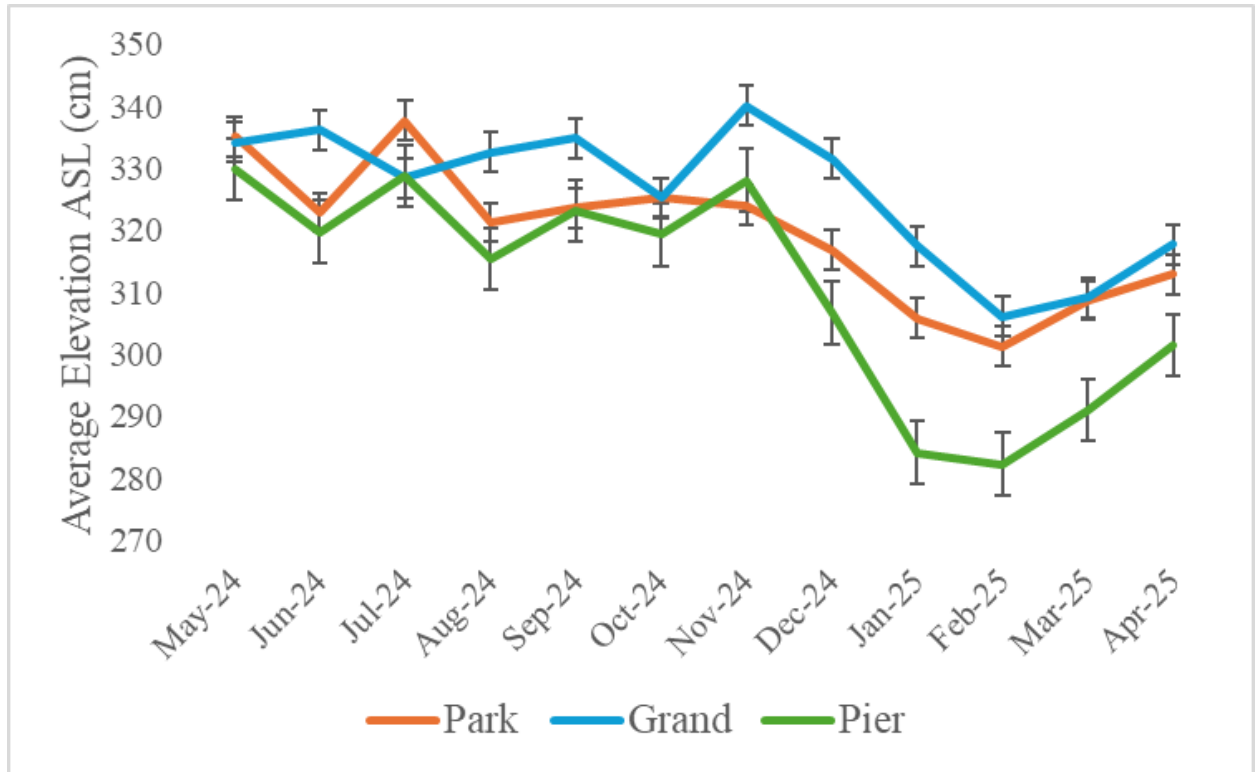


Figure 4. Monthly average beach elevation above sea level (ASL) at the three study sites. Error bars show mean $\pm$ 1 standard error. All sites showed a modest but synchronous dip in elevation between December and February, aligning with peak winter swell activity and suggesting short-term erosion followed by seasonal recovery. Each site was standardized such that 0 cm ASL is the lowest elevation at each site.

The two-way ANOVAs dissect the relative influence of space and time on sand metrics at Pismo Beach. For sand volume, the highly significant site effect ($p < 0.001$) and negligible month effect ($p = 0.934$) corroborate the visual stability at the Park and Pier sites in Fig. 3. Conversely, average elevation is shaped by both factors: modest but significant spatial differences ($p = 0.031$) overlay a clear temporal pulse ($p = 0.004$) that aligns with the winter erosion-accretion cycle seen in Fig. 4.

Table 1. ANOVAs of spatial and temporal factors impacting the amount of sand on Pismo Beach.

Effect on Sand Volume			
Variable	F	df	p
Site	14.5	2	<0.001
Month	0.417	11	0.934
Site*Month	0.632	22	0.758
Effect on Average Elevation			
Variable	F	df	p
Site	3.88	2	0.031
Month	5.26	11	0.004
Site*Month	0.549	22	0.898

Discussion

The modest yet statistically significant 4–6 cm decrease in mean elevation observed between December 2024 and February 2025 underscores the capacity of short-duration winter swells to alter beach topography on an otherwise accreting shoreline. Because all three sites rebounded to pre-storm levels by April, the data suggest that Pismo Beach possesses sufficient sediment supply for rapid recovery (Johnston et al.

2023; Drago et al. 2021). Such quick adjustment aligns with previous UAV-based surveys of California beaches that documented centimeter-scale erosion followed by seasonal infill within a single spring–summer cycle (Warrick et al. 2019). The parallel temporal trajectories between the Park and Pier sites (non-significant site*month interaction) further imply that storm-driven elevation changes operate at a scale ranging a few kilometers rather than being controlled by local morphology alone.

Relative volume remained remarkably stable throughout the 12-month record, with no significant monthly effect detected (Table 1). While this study provides useful insight into short-term patterns of sand movement at Pismo Beach, it represents only a single year of data, and it remains unclear how typical these conditions were.

Nonetheless, this approach—combining UAV photogrammetry with ground truthing—offers a cost-effective and scalable way to begin quantifying beach dynamics. Continued multi-year monitoring will be essential to capture interannual variability and build a more comprehensive understanding of sediment behavior and coastal resilience. The strong effect of site ($F = 14.5$, $p < 0.001$) potentially highlights persistent cross-shore gradients in sand storage, which may reflect persistent geomorphic influences, such as along-shore transport patterns or variations in dune connectivity—factors that have been shown to structure sediment distribution on other embayed beaches (Young et al. 2018; Defeo and McLachlan 2005). However, confirming these drivers would require direct measurement of transport rates and dune exchange over longer timescales. Comparable spatial structuring has been observed on other California embayed beaches, where physical features such as headland shadowing reduce wave energy in certain areas, and rip-cell circulation patterns create zones of sediment deposition. These processes lead to

predictable areas of sand accumulation and erosion, shaping long-term beach morphology (Defeo et al. 2021). Understanding these mechanisms is important because they help explain why certain sections of coastline consistently retain more sediment—information that can inform site-specific coastal management and habitat conservation efforts (Young et al. 2018). Thus, while storm waves temporarily lowered beach surfaces, they did not produce a measurable net loss of sand volume within the study domain.

The consistent spatial differences in sand volume across sites—particularly the persistent high volumes observed at Park Avenue—suggest that sediment gradients may not be uniform along Pismo Beach. Instead, they may reflect the influence of physical features such as dune connectivity, wave shadowing, or along-shore transport convergence that create localized accretion zones. Future modeling efforts, especially those incorporating nearshore hydrodynamics and sediment transport pathways, could help identify these potential “sand retention hotspots.” These models would generate spatially explicit hypotheses that could be tested with continued UAV-SfM monitoring, helping to build predictive capacity for beach change and inform site-specific management interventions.

Taken together, the elevation and volume results suggest that Pismo Beach may exhibit characteristics of a resilient sandy system under the conditions observed during the study period. The absence of substantial winter volume loss hints that sediment inputs—whether fluvial, aeolian, or along-shore (Angnuureng et al. 2023)—could be sufficient to offset seasonal erosion. However, this interpretation is based on a single year of data, and it remains unclear whether the 2024–2025 winter represented typical conditions. Similar short-term resilience has been reported for other California beaches

(Warrick et al. 2019), but interannual variability in storm intensity and sediment supply can significantly alter beach dynamics. As such, longer-term data are needed to determine whether this apparent balance is consistent or transient.

Pismo Beach supports ecologically important sandy beach habitat for species of conservation and recreational interest, including the federally threatened western snowy plover and the Pismo clam. The relatively stable sand volume and rapid post-winter elevation recovery observed in this study are encouraging signs for the persistence of key habitat features at Pismo Beach. For snowy plovers, elevation rebound and preserved low-slope profiles suggest that nesting areas may remain viable even after winter swell activity. For Pismo clams, the absence of net sediment loss implies that suitable substrate may be retained despite seasonal disturbance. While this study did not directly measure biological responses, the geomorphic trends observed align with conditions known to support both species. Future work combining sediment monitoring with integrated ecological surveys could more directly assess how physical changes translate into shifts in species distribution and abundance.

The relatively stable sand volume and rapid post-winter elevation recovery observed in this study are encouraging signs for the maintenance of key habitat features at Pismo Beach. For snowy plovers, the preservation of low-slope profiles and elevation rebounding suggests that nesting zones may remain viable despite seasonal storm impacts (Udhaba Dora et al., 2012). For Pismo clams, the apparent absence of net sediment loss implies that suitable substrate may be retained even through winter swell events. However, this study captured just one annual cycle and did not assess ecological responses directly. Without longer-term data, it is unclear whether the winter of 2024–25

represents a typical erosion-recovery pattern or a temporary condition. Moreover, localized changes in grain size distribution—which were not measured here—could significantly alter habitat suitability for clams (Bateman and Bishop, 2016). Continued monitoring over multiple years, ideally with integrated biological surveys, will be essential to understanding how physical beach dynamics shape habitat availability and resilience for these species over time.

These findings also have implications for the ecosystem services and recreational uses that Pismo Beach supports. Wide, stable sandy beaches offer natural shoreline protection (Pucino et al., 2021), habitat for invertebrates (Seitz et al., 2014) and shorebirds (Lafferty, 2001), and cultural value through activities such as walking, wildlife viewing, and clam harvesting (Marquardt, 2022). The southern section of the beach also hosts a designated OHV recreation area, which can increase sand compaction and dune disturbance—factors known to affect both geomorphology and habitat quality (Schlacher and Morrison, 2011; Defeo and McLachlan, 2013). The relative stability in beach volume and seasonal recovery in elevation observed across all three sites suggest that, at least over the short term, the system is withstanding current pressures such as winter storm activity, recreational use, and ongoing dune impacts. However, because this study did not directly measure sediment compaction or grain size, the effects of OHV use on physical habitat quality remain unassessed. Climatic stressors such as sea-level rise and increasingly frequent extreme wave events may also strain the system's capacity to recover in future years. While these data offer some short-term signs of resilience, continued monitoring will be needed to evaluate whether these ecosystem services remain sustainable as environmental and human pressures intensify.

Several constraints temper these conclusions. First, the 12-month duration captures only one winter season; inter-annual variability in swell climate may produce different responses (Novais, 2023). In particular, the 2024–25 winter did not experience extreme swell events like those recorded in the 2022–23 and 2023–24 seasons. As a result, the baseline conditions measured here may already reflect a system that had undergone substantial adjustment from earlier high-energy winters, meaning current observations could underestimate the scale of past changes or the system’s longer-term variability. Second, volume estimates are referenced to an arbitrary datum rather than absolute shoreline position, limiting direct comparison with lidar-derived budgets. This can obscure elevation-based changes that may be ecologically or geomorphologically meaningful. Other studies have addressed this challenge by integrating real-time kinematic (RTK) GPS data tied to national vertical datums, or by co-registering SfM models with coastal lidar datasets to anchor models to absolute elevation frameworks (Warrick et al. 2019; Novais et al. 2023). Incorporating such approaches in future work would improve spatial consistency and allow for broader cross-site or cross-study comparisons.

Although UAV-SfM provides centimeter-scale resolution, positional error in ground control points ($\sim\pm 5$ cm) introduces uncertainty that is on the same order as some of the measured elevation changes—particularly the 4–6 cm seasonal dip observed during the winter months. As a result, small changes in elevation may fall within the margin of error, limiting confidence in detecting subtle but potentially meaningful shifts in beach morphology. This uncertainty does not invalidate the observed trends, especially given their consistency across sites, but it does warrant caution in interpreting fine-scale

vertical changes as ecologically or geomorphologically significant without additional validation.

Additionally, sediment grain-size distributions and along-shore transport rates were not measured, which limits the ability to identify the physical drivers underlying the observed spatial differences in sand volume and elevation (Novais, 2023). For example, the consistently higher sand volume at Park Avenue could result from finer grain sizes, differences in sediment supply, or local transport convergence—but without grain-size or transport data, these remain speculative. This gap constrains the interpretation of spatial structuring as more than correlation, and highlights the need for future studies to pair morphological data with sedimentological and hydrodynamic measurements to build a mechanistic understanding of beach behavior.

This study demonstrates that monthly UAV-SfM surveys can resolve both transient elevation drops from winter storms and persistent spatial gradients in sand volume. At Pismo Beach, the 2024-25 swell season induced short-lived surface erosion without depleting the overall sediment budget, indicating a resilient coastal sand store during this year. This study demonstrates that UAV photogrammetry paired with ground truthing offers a cost-effective, scalable method for tracking beach dynamics. While findings from a single year suggest resilience, continued multi-year monitoring will be essential to capture interannual variability and assess long-term coastal stability. Continued multi-year monitoring, coupled with wave-climate and sediment-transport measurements, will be essential for anticipating how future climatic shifts may alter this balance and for informing adaptive coastal-management strategies.

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