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THESIS

SEDIMENT TRANSPORT ASSOCIATED WITH EPHEMERAL RIVER BREACHING AND CLOSING EVENTS

by

Walter R. Young

June 2018

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13. ABSTRACT (maximum 200 words)

Breaching of beaches is a catastrophic morphological change that can fundamentally alter the circulation within littoral systems and create damage to surrounding coastal infrastructure. At ephemeral rivers with intermittent seasonal river discharge, rivers undergo breaching and closure events that result in significant morphological evolution, and to quantify this evolution, beach elevation must be measured through beach and bathymetric surveys. To better understand the volume, rate, and direction of the sediment transport, and to determine if the seasonal excavation to artificially breach the Carmel River State Beach to avoid flooding of adjacent residences to the river lagoon is necessary and effective, the breaching cycle was observed during the winter months of 2017-2018. The methodology of surveying the beach using Structure from Motion with an unmanned aerial vehicle (UAV) was utilized for the rapid beach morphology assessment with centimeter accuracy, which can be applied to future civilian and military operations even in remote and inaccessible areas or contested beaches. Digital Elevation Model analysis revealed that the sediment was primarily transported onto the back beach alongshore due to wave overwashing and the artificial breaching was ineffective in maintaining an open breach and caused a more-rapid outflow of the secondary natural breach, which could be harmful to indigenous aquatic wildlife and their habitat.

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SEDIMENT TRANSPORT ASSOCIATED WITH EPHEMERAL RIVER BREACHING AND CLOSING EVENTS

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ABSTRACT

Breaching of beaches is a catastrophic morphological change that can fundamentally alter the circulation within littoral systems and create damage to surrounding coastal infrastructure. At ephemeral rivers with intermittent seasonal river discharge, rivers undergo breaching and closure events that result in significant morphological evolution, and to quantify this evolution, beach elevation must be measured through beach and bathymetric surveys. To better understand the volume, rate, and direction of the sediment transport, and to determine if the seasonal excavation to artificially breach the Carmel River State Beach to avoid flooding of adjacent residences to the river lagoon is necessary and effective, the breaching cycle was observed during the winter months of 2017-2018. The methodology of surveying the beach using Structure from Motion with an unmanned aerial vehicle (UAV) was utilized for the rapid beach morphology assessment with centimeter accuracy, which can be applied to future civilian and military operations even in remote and inaccessible areas or contested beaches. Digital Elevation Model analysis revealed that the sediment was primarily transported onto the back beach alongshore due to wave overwashing and the artificial breaching was ineffective in maintaining an open breach and caused a more-rapid outflow of the secondary natural breach, which could be harmful to indigenous aquatic wildlife and their habitat.

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LIST OF ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
GCP	Ground Control Point
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
MPWMD	Monterey Peninsula Water Management District
MVS	Multi-View Stereo
RTK	Realtime Kinematic
SfM	Structure from Motion
UAV	Unmanned Aerial Vehicle

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I. MOTIVATION

The ability to better understand and operate in the littoral environment as well as the further utilization of unmanned systems is one of the key concepts in the Chief of Naval Operations objectives for the future Navy (Richardson 2017). This includes both near-shore maritime, amphibious, riverine, and disaster relief/humanitarian assistance operations. The environment is dynamic in the littorals, and understanding the processes affecting properties such as coastal currents, changes in salinity due to fresh water runoff and interaction of water masses, and changes to coastal/river bathymetry make the challenge even greater. As a military oceanographer, hydrographer, and amphibious operations planner, I wanted to provide more insight into beach morphology to help improve planning for future U.S. Navy and Marine Corps operations.

Sediment transport is important to understanding changes to river bathymetry which is crucial when planning and executing riverine operations. Changes to beach topography and beach suitability is also important in the planning and execution of amphibious operations. By perfecting the Structure from Motion mapping method, quick and inexpensive change detection surveys can be conducted on areas near ephemeral river associated beaches using military unmanned aerial vehicles (UAV) to determine if any changes have occurred due to breaching or closing of the beach, and potentially forecasting where the sediment transport will occur.

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II. INTRODUCTION

Sediment transport is a key factor in determining the morphology of tidal inlets in which river or tidal outflow is cyclically balanced by saltwater tidal inflow to establish sand bars in the channel. The placement of the sediment deposit not only will be determined by the episodic balance of the inflow and outflow but also by the preferential flow determined by bathymetry (Fitzgerald 1996; Ralston et al. 2012). In contrast to tidal inlets, ephemeral rivers are seasonally closed off to the ocean as a result of buildup of sediment that forms a beach at the coastal boundary of the river that separates the river mouth from the adjacent coastal ocean (Davidson et al. 2008; Laudier et al. 2011). Such ephemeral rivers are found most often in regions with Mediterranean climates with dry summer and early fall months and increased precipitation in late fall and winter months (Behrens 2013). When the river lagoon water levels rise due either to ocean wave overtopping caused by seasonally increased, cross-shore wave heights or to upstream river discharge caused by seasonally increased precipitation, breaching of the beach occurs (Pierce 1970; Kraus, N. and Munger 2008; Scooler 2017). Breaching from the ocean side can be accelerated by increased waves and storm surge that scours the beach and elevates lagoon levels (Kraus et al. 2002; Kraus and Wamsley 2003; Sallenger et al. 1985).

A more accurate method of predicting a breach event is to monitor ocean significant wave heights, tidal data, river flow and elevations, and sediment transport due to wave overtopping (Behrens et al. 2009; Scooler 2017). Likewise, by monitoring the sediment transport, the beach morphology and cyclic closing of the beach can be better understood and can help answer long-term trends in sediment loss or gain to a particular system. While many methods exist to obtain changes to the beach topography, conducting traditional terrestrial Global Positioning System (GPS) mapping requires personnel to have access to the beach and in military applications requires a man in the battlespace. Aerial methods such as Light Detection and Ranging (LiDAR) are not cost effective and require a large logistical footprint for expeditionary operations. Structure from Motion (SfM) can provide high-resolution 3D imagery using Multi-View Stereo (MVS) technique (Figure 1) and is both time and fiscally efficient (Johnson et al. 2014) and allows for use of autonomous aerial vehicles to reach forward into difficult terrain (Carrivick et al. 2013). SfM-MVS collection and processing techniques can be optimized to create orthomosaics and Digital Elevation Models (DEMs) (Figure 2) that, when compared temporally, can show changes in beach topography. Previous studies using this method have been conducted to monitor flooding along an ephemeral river (Smith et al. 2014), but not in observing the breaching and closure of a beach associated with the ephemeral river.

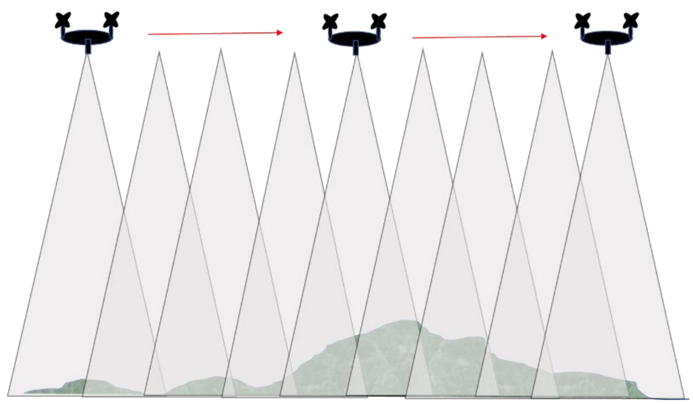

Figure 1. Structure from Motion (SfM) Using a UAV

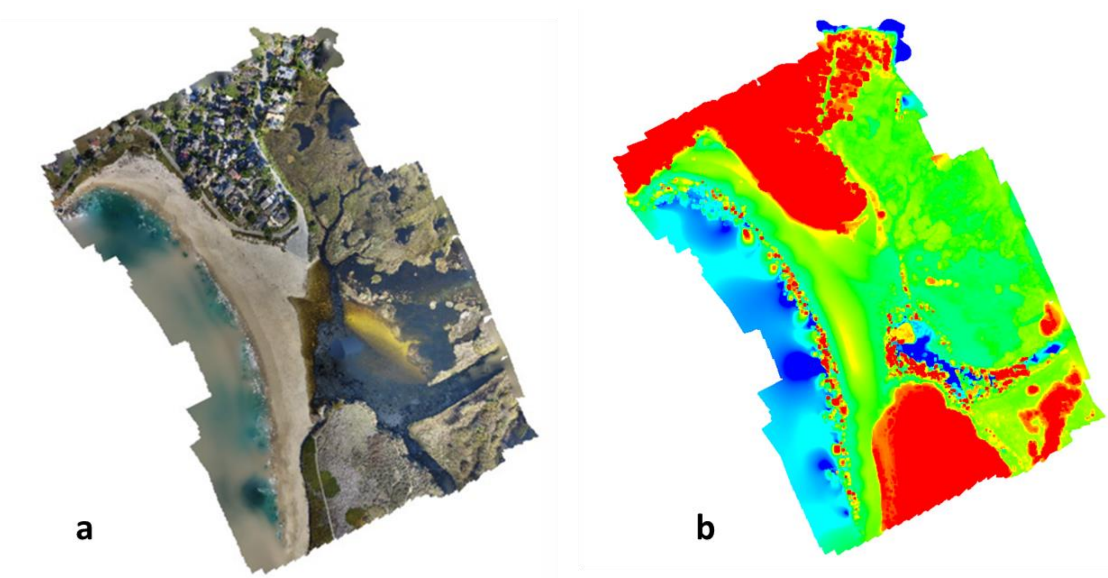

Figure 2. (a) Orthomosaic and (b) Digital Elevation Model examples from SfM

Carmel River State Beach is at the mouth of the Carmel River (Figure 3), located on California's central coast, and seasonally breaches during the wet winter months. The mouth of the river forms a lagoon and brackish water marsh that is bordered by houses in the Carmel-By-the-Sea, CA community to the north. In early winter, as the water levels of the lagoon begin to rise, Monterey County Resource Management Agency often conducts an artificial breaching of the lagoon in the ocean by dredging a small channel to alleviate community concerns. Follow up studies to determine if these breaches are necessary or how quickly the pre-dredging water levels return during the episodic closing and re-breaching of the beach have not been conducted.

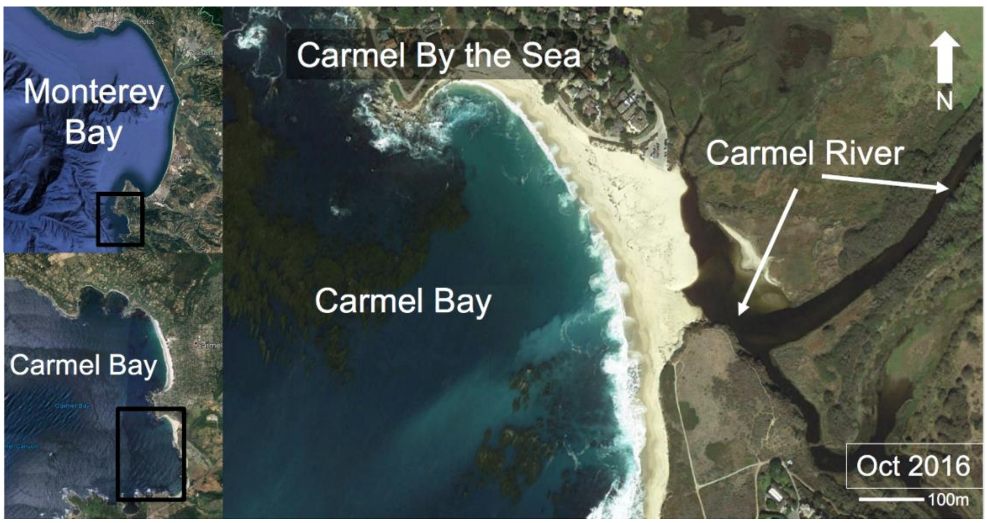

Figure 3. Location of Carmel Bay, CA and the Carmel River.
Source: Scooler (2017).

The hypothesis of this research is that artificial channel development to control breach intensity (rate of water level drop) is short-lived owing to rapid sediment transport associated with the intermittent breaching at the initiation of the rainy season. Furthermore, relaxation of the sediment alterations is rapid and does not ultimately alter the intermittent breach-closure cycle. It is proposed that such methods are not cost effective and alternative measures could be adopted to control flooding to the surrounding community. In addition, winter wave climates contribute to a net onshore migration of the beach that is balanced by offshore transport at the breach.

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III. INSTRUMENTATION AND DATA COLLECTION

Beach elevation data was collected using UAV surveys and walking GPS surveys of the beach to monitor topography, and river hydrographic surveys were conducted to collect bathymetry data. The UAV survey using GPS-referenced ground control points was the primary method for collecting data to detect morphological change during the breaching cycle using Structure from Motion (SfM). Because the GPS has high horizonal and vertical positioning accuracy, a GPS walking survey was compared to the UAV survey to quality control check for any significant errors in elevation and positioning. The data collection was executed from November 2017 through February 2018 to monitor changes to the lagoon leading up to the breaching of the beach and the entire cycle of the opening and closing of the breach.

A. UAV STRUCTURE FROM MOTION SURVEY

The UAV surveys were conducted using a DJI Phantom III Advanced quadcopter (Figure 4), which has a twelve megapixels resolution camera with a 1/2.3" sensor and f/2.8 prime lens. The UAV flights were flown at an altitude of 60 m at medium drone speed (5m/s) with a camera angle of 80 degrees (10 degrees off nadir) and fast mode triggering. The mapping software used was Pix4DCapture. A single grid survey pattern with 80% along track and 70% side overlap of imagery that is recommended for analyzing the data with Agisoft Photoscan software for SfM was used. The single grid pattern was then offset from the first flight by 90 degrees in order to mimic a double grid pattern for each survey. Three UAV surveys were conducted. The flights were not conducted using double grid mode owing to a consistent software glitch for flights requiring multiple batteries. A pre-breach survey was conducted on December 06, 2017, a breached beach survey on January 11, 2018, and a closed breach survey on January 23, 2018.

Figure 4. DJI Phantom 3 Advanced

To significantly improve the aerial survey accuracy from meters to centimeters, GPS-surveyed ground control points (GCP) were used. The GCPs were 2.5’x 2.5’ quarter-inch plyboards painted into quad panels of black and natural squares to give color contrast and precise center points for improved detectability in the imagery and positioning. The control points were surveyed in using an Ashtech ProMark GPS receiver on each point for a minimum of 5 minutes (Figure 5). The GPS accuracy was within +/- 0.5 cm and analysis of the positioning revealed a vertical and horizonal precision on the order +/- 5 cm (Figure 6). For the first two UAV surveys, six GCP and the final survey twelve GCP were deployed. The reason for the increase in the number of GCP placed for the final survey was to see if accuracy of digital elevation model produced from the data could be improved, and if the improvement would be worth the additional time to deploy and position each point.

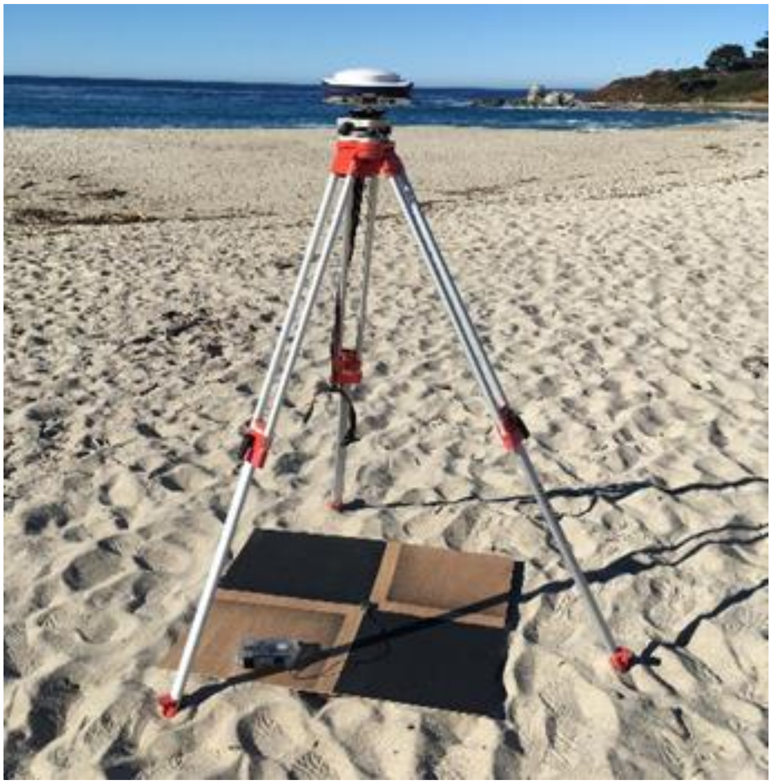


Figure 5. Ground Control Point with GPS Positioning

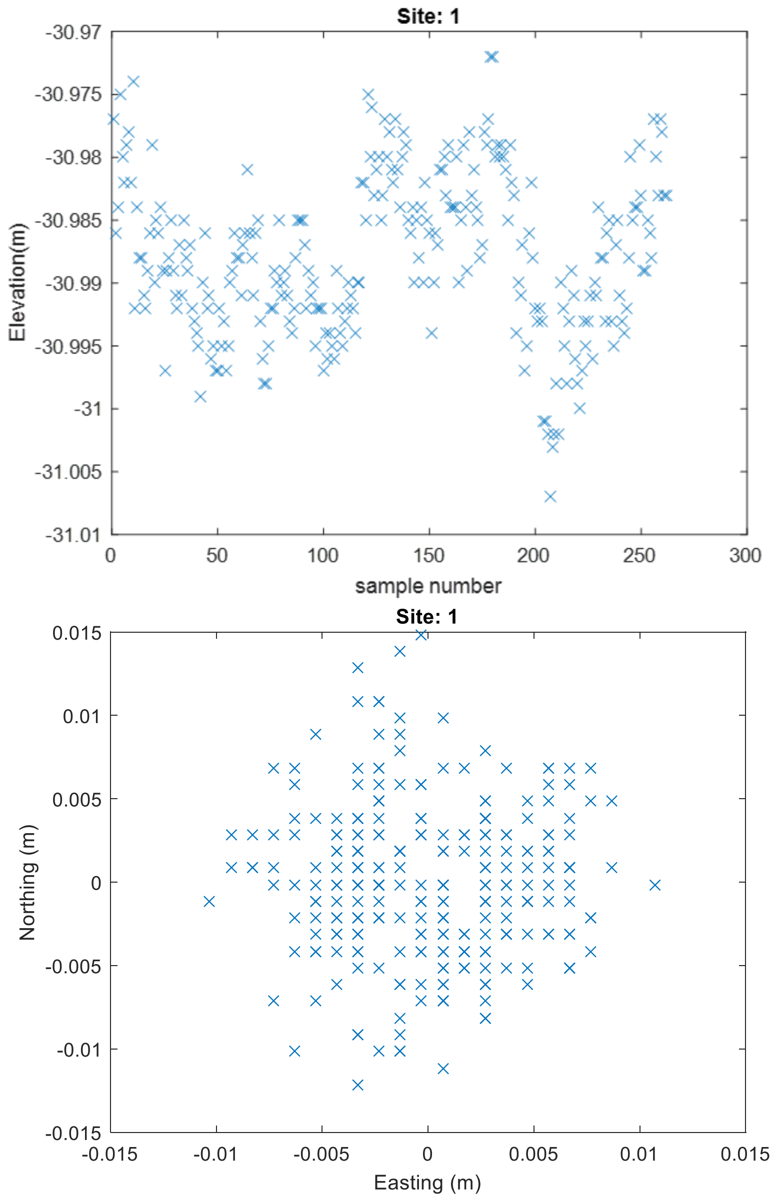


Figure 6. Precision Analysis of GCP Positioning

B. GPS WALKING SURVEY OF BEACH

The walking surveys utilized the same Ashtech ProMark 500 GPS antennae mounted on a pole attached to a body harness (Figure 7). Before each survey, height from ground to the antennae was noted and subtracted from the heights from the ellipsoid. Three walking surveys were conducted; an initial pre-breach survey on November 28, 2017; a breached beach survey on January 11, 2018; and a closed beach survey on January 23,

2018. Besides the inherent GPS error of the system, random error from the individual's walking gait, the slope of the beach, and the packing of the sand all contribute to systematic error of the beach topography.

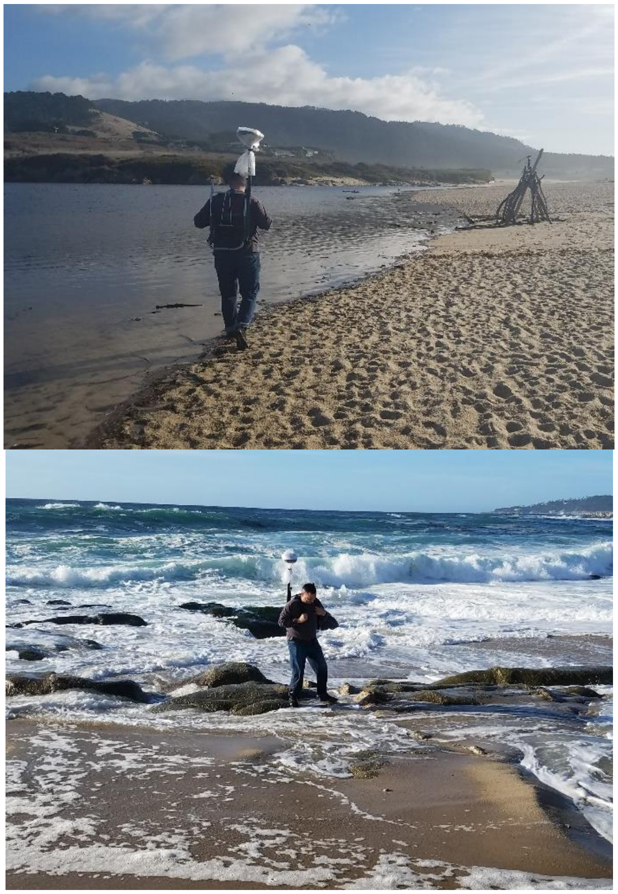


Figure 7. Walking GPS Survey Along Carmel River State Beach

C. BATHYMETRIC SURVEY OF LAGOON

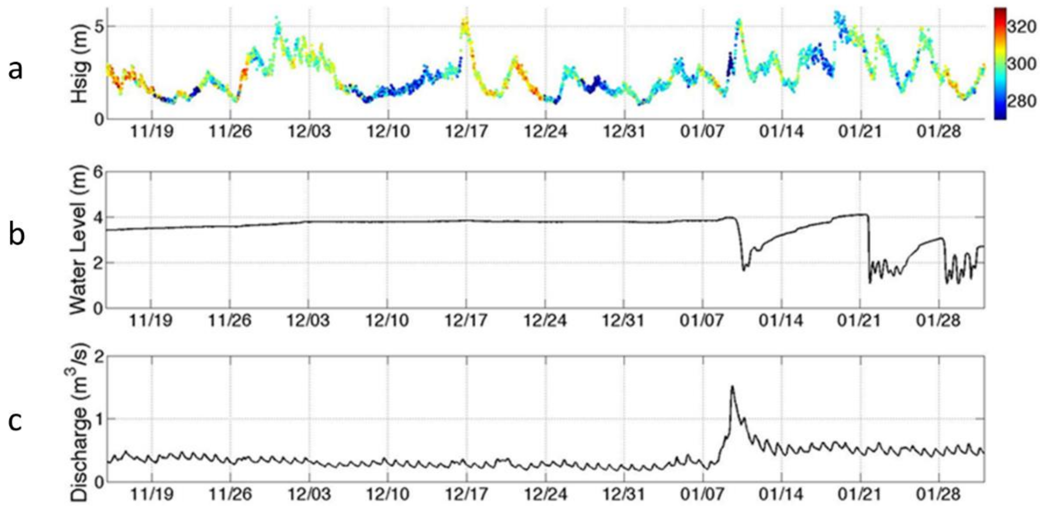
Bathymetric surveys of the lagoon were conducted to determine changes in the bathymetry caused by sediment transport. A SonTek RiverSurveyor M9 was used along with a GPS base station to get Realtime Kinematic (RTK) GPS accuracy in positioning. The RiverSurveyor is a nine transducer multibeam array system with 1% depth accuracy and 1mm depth resolution. A single person kayak was used to pull the RiverSurveyor in the lagoon (Figure 8). The hydrographic surveys were conducted on November 27, 2017 and January 11, 2018.

Figure 8. Conducting Bathymetry Survey Using RiverSurveyor and Kayak

The Monterey Peninsula Water Management District (MPWMD) monitors the Lagoon water levels with a surveyed water level gauge which was monitored to observe changes in lagoon depth to determine when breaching and/or closure of the beach might occur. The gauge accuracy is $\pm$ 0.015 m in comparison to a staff gage (James 2005). Reviewed data from 2014–2017, a breach typically occurs when the lagoon reaches an elevation of approximately 4 m, as likely constrained by beach elevation. All of December, 2017 and until January 8, 2018 there was little precipitation, and lagoon levels remained at 3.7 – 3.8 m. On January 8–9 water levels increased to 4 m with continued precipitation. However, in response to growing concerns of flooding to local residences in Carmel along with lagoon and river, the Resource Management Agency of Monterey County dredged a small breach of the south end of Carmel River State Beach in the early hours of January 9 (Figure 9 and 10), resulting in a rapid outflow and elevation drop of lagoon waters (Figure 11). According to the county workers, approximately 230 m^3 of sand was displaced to create a man-made breach.

Figure 9. Excavated Breach of the Beach (View from the North)

Figure 10. Sand Berm Resulting from Excavation of the Breach.



Adapted from James, G. email of MPWMD Carmel River Lagoon and Basin data to author, MA2018 and NOAA bouy data (2018).

Figure 11. (a) Carmel River State Beach significant wave height and direction, (b) lagoon water levels (NAVD88), and (c) river discharge.

IV. DATA ANALYSIS AND METHODOLOGY

A. CREATING DIGITAL ELEVATION MODEL

Structure from Motion (SfM) was used to create a 3D model solution of the survey area to compare the temporal changes in elevation resulting from sediment transport. SfM applies multiple view stereo (MVS) photogrammetry which takes images of objects from various angles/perspectives and 3D imaging software is used to find matching points in the images to allow for alignment of the individual images into a collective sparse cloud 3D model. The sparse cloud is then transformed onto a coordinate system to give the image points horizonal and vertical positions based on established datums by identifying GCPs in the imagery that have been surveyed into the datum. Once the GCPs are established the camera position of each image can be calculated and positioning and depth assigned to the image pixels using triangulation. With positioning information of each image identified, a complete dense cloud is generated. From the dense cloud a smoothed 3D mosaic and/or DEM can be created with XYZ positioning data (Hartley and Zisserman 2004; Pollefeyes and Van Gool 2002; Westoby et al. 2012)

A DEM was created from each UAV survey using Agisoft Photoscan version 1.4. The photos were imported and aligned using a WGS84 (EPSG::4326) coordinate system. Setting for photo alignment were “high” accuracy with a keypoint, defined features that are scale and rotation invariant that Photoscan identifies in each photo (Lowe 2004), and tie point, the number of identical key points that will be used to match positions between images for photos alignment (Snavely et al. 2008), limitations of 40,000 and 4000, respectively, and adaptive camera model fitting enabled. An initial lens calibration of the UAV camera was conducted and saved as the initial camera calibration factor setting for each survey. The GCPs were imported and positioning confirmed for each one. The GCPs were not fixed positions between the individual surveys; therefore, they had to be positioned for each chunk, a cluster of images used to create a 3D image. Any GCPs outside of the surveyed area were removed. Furthermore, 1–2 GCPs were not used as reference points for the project but were used as check points after the DEM was produced to check the accuracy of the DEM against known positions after production (Table 1). Once the reference points were positioned, a dense cloud was built using settings of "high" quality and "mild" depth filter setting. From the dense cloud a DEM was created with interpolation enabled and a resolution of 5.42 cm (Figure 12). The accuracy of the DEMs were then checked against the GCPs saved for check points (Table 2). The three DEMs were then exported as XYZ files with 0.1 m resolution for import into Aquaveo Surface-water Measuring Software (SMS) for further modification and to conduct volumetric calculations. A 1 m grid was used to interpolate all surfaces within SMS to the same XY points for direct comparison.

Table 1. GCP Root Mean Square Errors. X-Latitude, Y-Longitude, Z-Elevation.

Date of Survey	# of GCP	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
12/6/17	4	1.13	4.83	4.53	4.96	6.72
1/10/18	4	8.29	6.69	0.41	10.65	10.66
1/23/18	9	4.12	7.82	12.81	8.84	15.56

Table 2. DEM Check Points Root Mean Square Errors. X-Latitude, Y-Longitude, Z- Elevation.

Date of Survey	# of Check Points	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
12/6/17	2	2.89	3.68	4.40	4.68	6.42
1/10/18	1	23.02	13.54	1.95	26.71	26.78
1/23/18	2	3.18	4.61	16.34	5.60	17.27

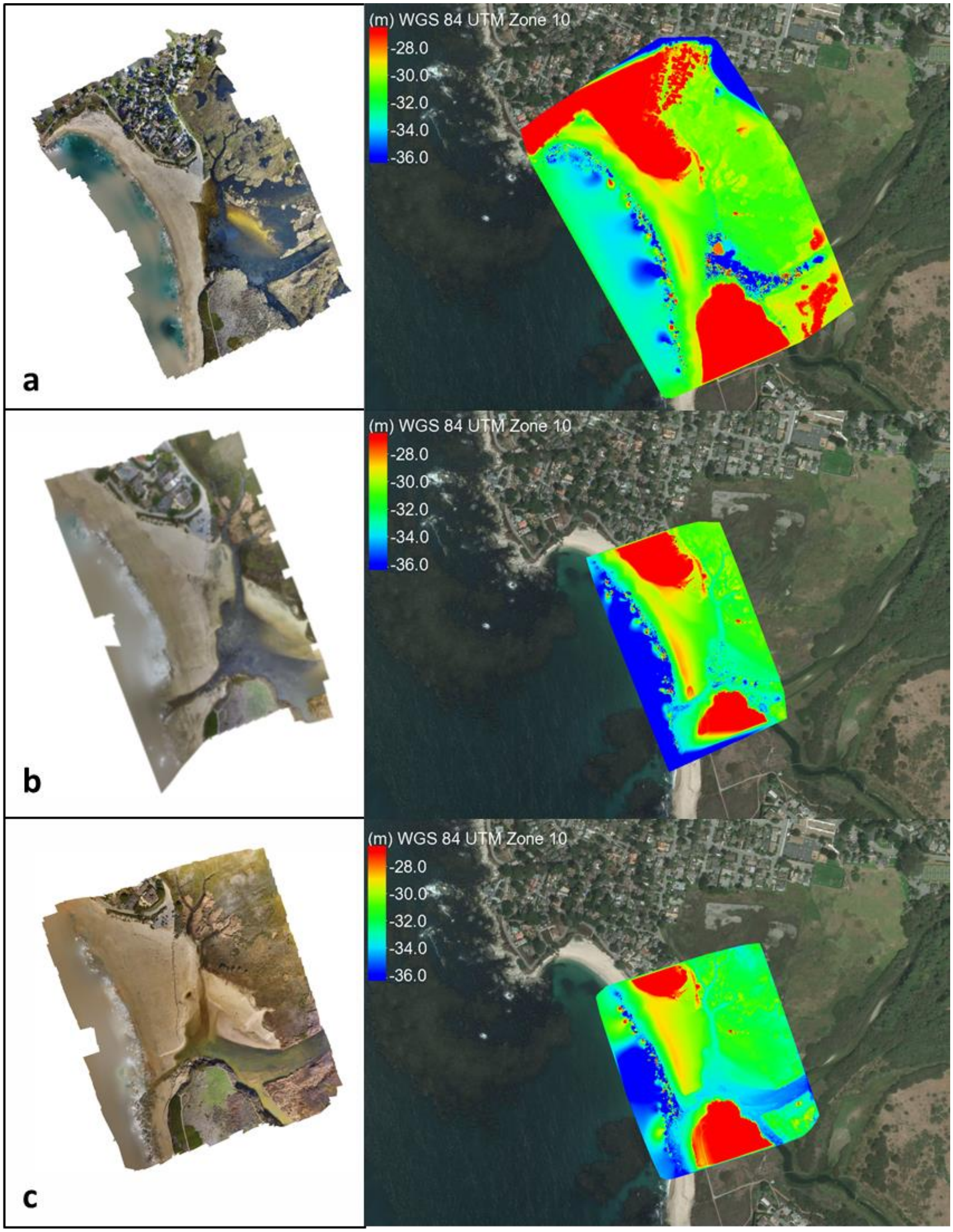


Figure 12. Orthomosaics (left) and DEMs (right) with elevations in meters (WGS84 UTM Zone 10) for (a) December 06, 2017 (b) January 11, 2018 and (c) January 23, 2018.

B. MERGING BEACH TOPOGRAPHY WITH LAGOON BATHYMETRY

The areas of a DEM that contains moving objects such as the surf and swash zones have inaccurate positioning and elevation values because there are not invariable temporal keypoints to identify features to align to, and refraction of light on water caused all elevations underwater to also be inaccurate. Therefore, those portions of the DEMs had to be removed, and the hydrographic lagoon depths were merged with the topographic data generated by the DEM to determine how much and where the beach sediment was transported into the lagoon during the breaching. It was assumed that the morphology of the lagoon bottom was not due to sediment transport from the river upstream.

C. COMPARING DEM WITH WALKING SURVEY

The walking survey GPS text files were imported, merged with the hydrographic data sets, and interpolated to create smooth surfaces surveys. The merged hydrographic GPS and DEM surfaces were then compared to further validate the DEM positioning and elevation accuracy (Figure 13). The two surfaces showed only centimeter differences in the areas of packed sand and decimeter differences in areas where sand waves existed and along the sand berm of the excavated side pile in which the sand was very loose and the individual had to walk up a steep slope, resulting in tilting of the GPS antenna. Therefore, the comparison demonstrated that the DEMs are within centimeter accuracy in elevation as previously was determined with the survey check points.

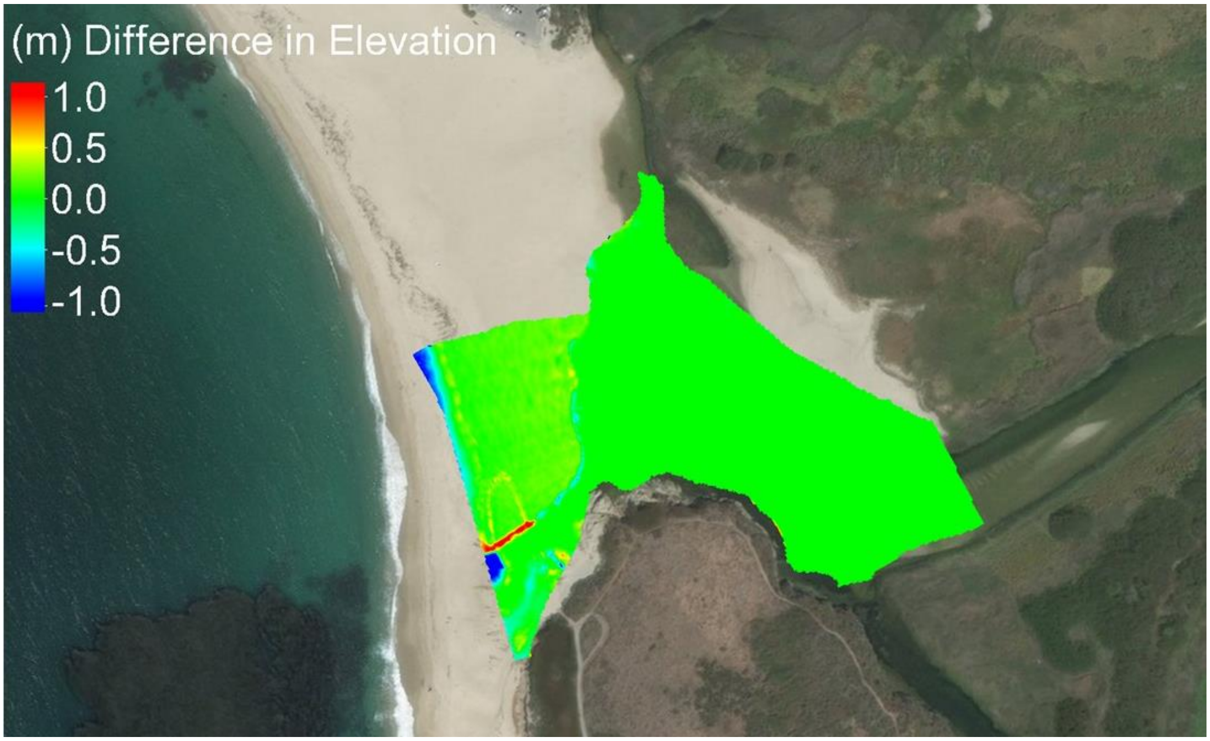


Figure 13. Comparison of elevations between January 11 DEM with bathymetry and walking survey with bathymetry

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V. RESULTS

Comparison of the three DEMs showed significant deposits of sediment on the top and back side of the beach as well as throughout the lagoon between December 06, 2017 and January 23, 2018. A net loss of sediment in the region of the breach and on the beach face was also demonstrated. The total net change in the region of interest was an approximately 2860 m^3 gain of sediment (Figure 14).

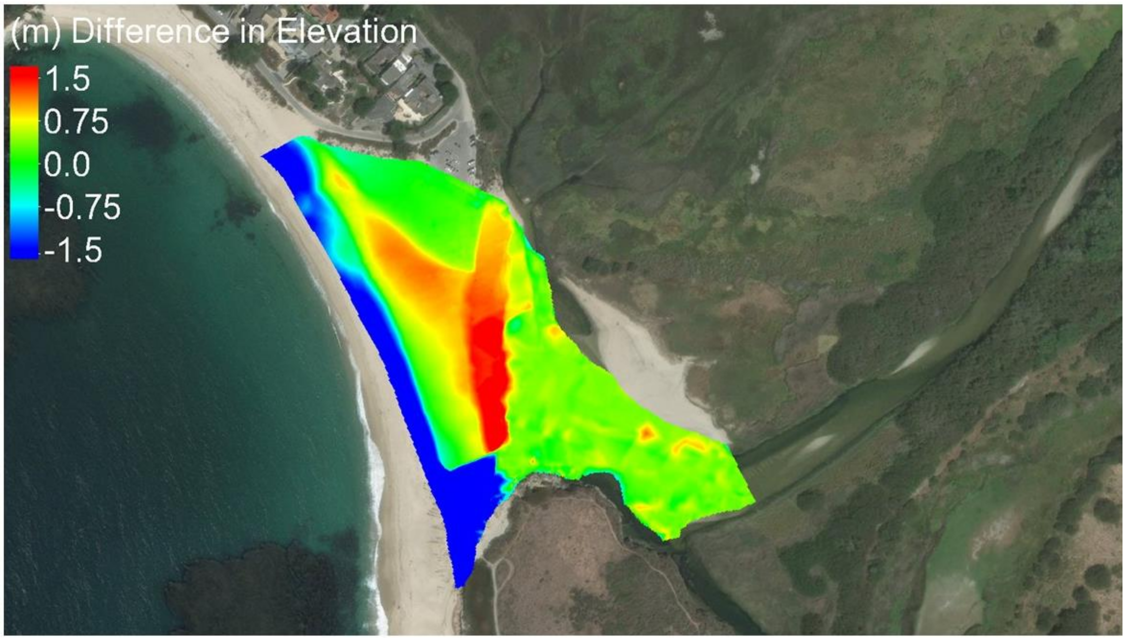

Figure 14. Change in elevation from December 06 to January 23 at Carmel River State Beach

A. THE BEACH

The area of the beach that was not dredged showed a net gain of sediment of approximately 5190 m^3 (Figure 15). The pattern of sand deposit shows that the northern edge of buildup was along a pre-existing crest that was the reminisce of a berm created from the breaching of the beach in the 2017 winter season (Figure 16) and bound to the west by the crest of the beach oriented along its northwest to southeast axis. The majority of the sediment gain was along the lagoon water edge.

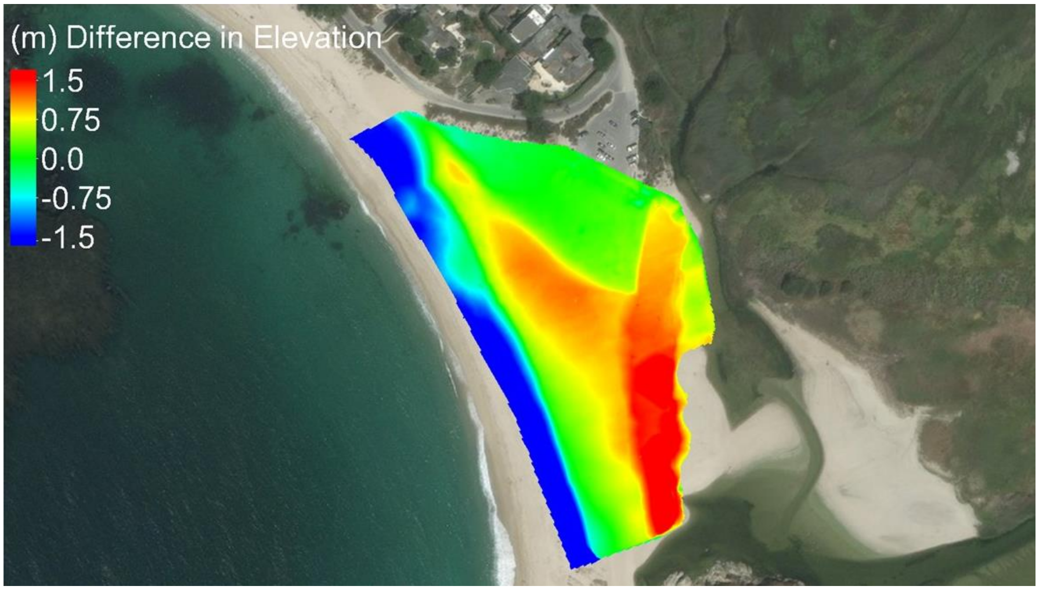

Figure 15. Change in elevation of the beach from December 06 to January 23

Figure 16. Northern crest of beach from 2017 breach of the Carmel River (Viewed from lagoon looking seaward)

B. THE BREACH

The area that was dredged on January 9, 2018 widened significantly over the two weeks until the final survey on January 23 which was restricted to a northern migration because of rock outcrops and step sand berms and cliffs on the southern side of the breach, and the breach went through a series of openings and closings primarily driven by river discharge filling the lagoon and wave action once the lagoon water elevations dropped below 2 meters. There was a net loss of sediment of approximately 7400 m^3 (Figure 17).

Figure 17. Change in sediment elevation in area of the breach from December 06 to January 23.

C. THE LAGOON

The most surprising result was the large net gain of sediment of approximately 5070 m^3 distributed throughout the lagoon over the course of the observations (Figure 18). The areas of greatest sediment deposit were in the vicinity of rock outcrop at the base of the cliffs in the southern portion of the lagoon and areas of organic debris and vegetation along the northern shore.

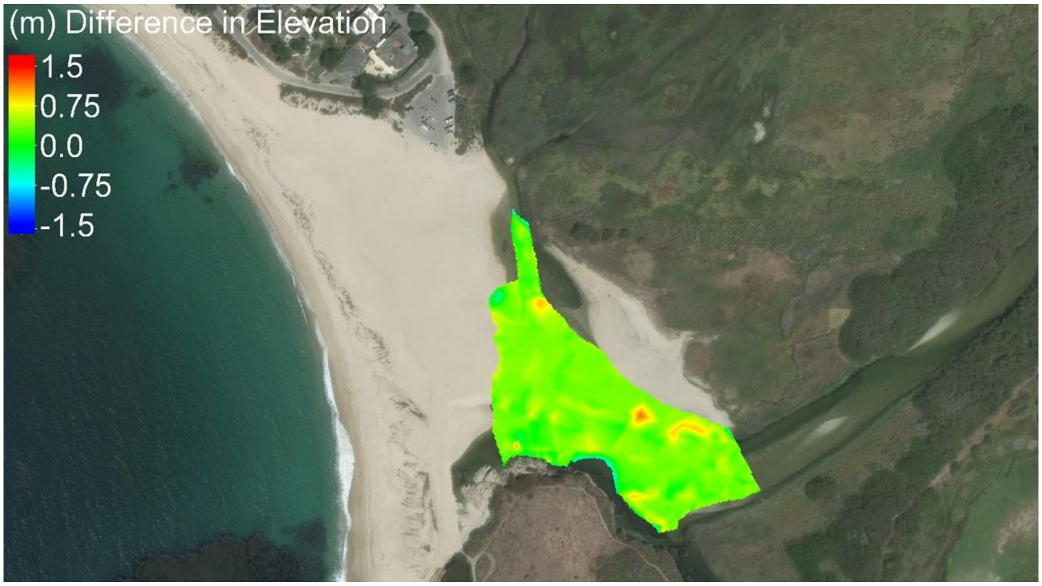

Figure 18. Change in elevation of the beach from December 06 to January 23

VI. DISCUSSION

The observations showed a net gain of sand in the area of the beach and lagoon which indicates that the area under consideration is not a closed system. Due to the wide area and depths of the bay adjacent to the beach and the expected thin layer deposition, it would be almost impossible to monitor millimeter changes to the bathymetry from sediment transport onshore onto the beach and into the lagoon via overwashing. Instrumentation available for our research did not allow for an accurate measurement of sediment transport that may be flowing into the lagoon itself during increased seasonal precipitation and river discharge since the removal of an upstream San Clemente Dam in 2015 and smaller Old Carmel River Dam in 2016. Future studies upstream of the lagoon would be helpful in determining exactly what degree of contribution the river is providing to the overall sediment buildup into the lagoon.

The majority of influx of sediment in the system (14,000 m^3) was found on the inshore slope of the beach and along the lagoon water edge where a steep sand berm formed from both the decrease in water elevation (>2 m) and deposition of sand over a period of a month (Figure 19 and 20). The pattern of the sediment transport onto the beach was consistent with that expected of a beach with a crest closer to the shoreline with steepening foreshore and mild to gentle sloping backshore (Jimenez, J., A.H.Sallenger, and L. Fauver 2007). From December throughout January, a steady increase in significant wave heights to a maximum of over 5 m on January 19 just prior to the final survey and cross-shore direction from 290 to 310 occurred. These wave conditions allowed for increased wave-induced sediment transport caused by beach overwashing, an established feature of Carmel River State Beach (Laudier et al. 2001; Scooler 2017), in which significant amounts of seaside shoreline is eroded into the surf zone, approximately 8500 m^3 in this case, and then redeposited beyond the crest onto the backshore as the wave is unable to return back to sea but instead slowly flows down the backshore slope into the lagoon and rapid downslope flow depositing sediment into the back barrier watershed in the event of significant overflow (Baldock et al. 2007), approximately 13,700 m^3 of sand on Carmel River State Beach.

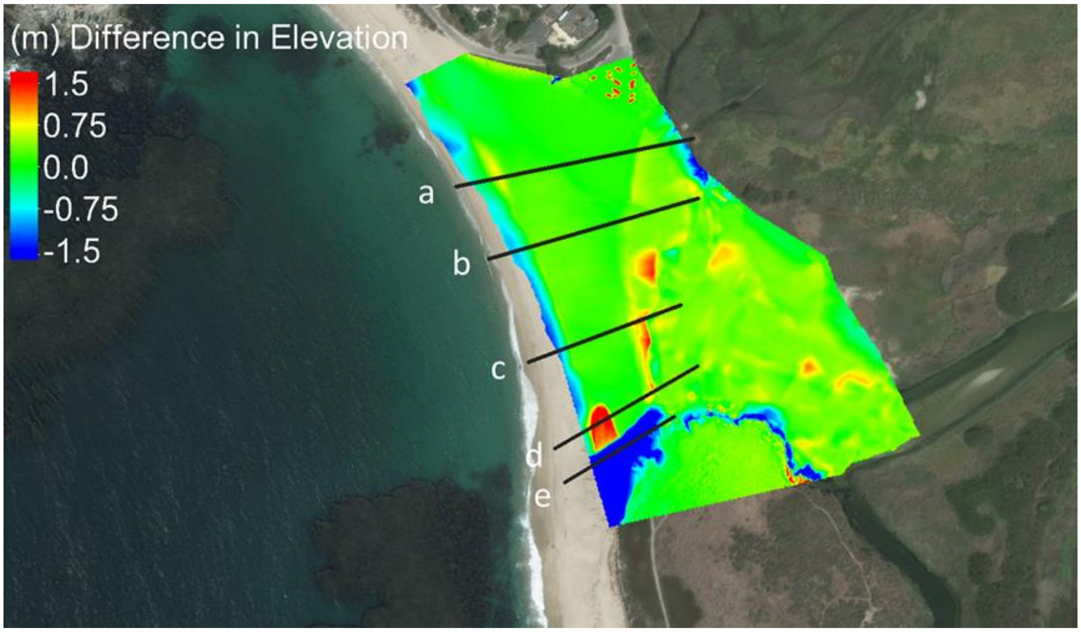

Figure 19. Map of elevation cross sections.

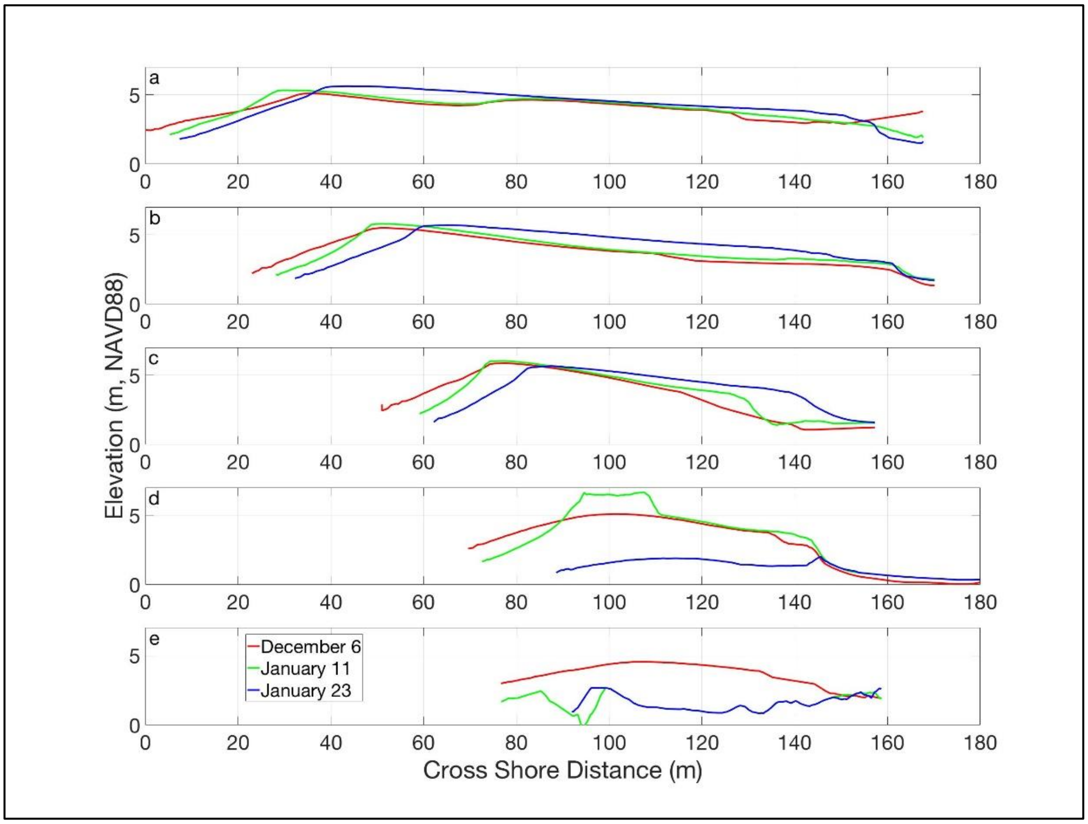

Figure 20. Cross shore elevation changes of the three DEMs.

The difference in the amount of sediment eroded away from the beach versus the amount deposited can also be explained by a rapid outflow of sediment from the breach, net total of 7500 m^3, that occurred on January 9 after the initial mechanical breach, and again on January 22 just prior to the final survey (Figure 11). Based on established littoral sediment transport processes, the sediment from the breach would have primarily moved into the surf zone for weak jets, or offshore if the jet from the river penetrated the surfzone and wave action was insufficient to contain the offshore flow (Hicks, D.M and Inman, D.L. 1987). Furthermore, because the surfzone is unconducive to accurate elevation estimates from SfM (or walking surveys), that portion of the DEMs was removed, but scouring in that region may have also attributed to the total amount transported from the surf zone on the backshore (Figure 21).

Figure 21. Scheme of sediment transport in the littoral system.

Overall results did reveal that the mechanical breaching of the southern portion of the lagoon was effective in drastically reducing the lagoon water levels that threaten adjacent homes. However, forcing a breach was unnecessary and was less effective in maintaining the breach geometry and duration when compared to the natural breach that occurred on January 22. Analysis of the water levels demonstrate that the breach closed within 48 hours and water levels began to rise (Figure 11b), indicating that the mechanical breach was ineffective in maintaining the breach, but the natural breach that followed on January 22 maintained a pattern of shallow sand deposition that allowed the system to maintain a pattern of opening and closing throughout the observation period (Figure 11). Furthermore, the mechanical breach resulted in looser sand compaction at the breach site which resulted in a more rapid breaching directly across the beach on second major breach and increased out flow as indicated by the steeper decline in lagoon water levels. This rapid outflow may result in the transfer of biologicals from the lagoon into the ocean. The day of the mechanical breach, the lagoon water levels were within a meter from height of the crest of the southern portion of beach were the breach was created, and had the breach been allowed to occur naturally, the sediment transport would have occurred more slowly and reduced the rate of outflow.

A majority of the sediment transport occurred from the breach and deposited in the back beach slope and lagoon water edge. Future surveys should be conducted to observe the long-term beach morphology and migration at Carmel River State Beach. As the backshore slope begins to fill in over time and the sediment reaches a level state with the northern crest, it should result in more beach stability as the washover will decrease and increased wave runup in the seaside swashzone will cause increased scouring in the winter season. When the back beach reaches a near level state with the beach crest or wave and tidal forces decline to point of not achieving overwash, the inflow of water from the ocean into the lagoon will cease and the breaching cycle should end with final closure of the breach (Scooler 2017).

Because single beam vertical profile depths were used for the water depths, during interpolation of a smooth surface, areas between the survey lines were linearly interpolated using 1 m resolution grid cells which is source of potential error in the bathymetric data determining changes in sediment in the lagoon. In the initial hydrographic survey, the kayak did not survey along the coast that resulted in having to apply scatter points with linear values between the coast and the nearest lagoon bathymetric data point which is another source. As a lesson learned, the remaining surveys did survey the water edge and it is recommended that all follow on hydrographic surveys employ this method.

Structure from Motion was found to be an excellent way to rapidly survey changes to the beach morphology with centimeter accuracy assuming that you apply several procedures in your methodology. Much was learned about the methodology of using SfM for observing beach morphology during this experiment. Assessing fixed reference points within the survey area will allow surveying the points in the initial survey and then apply them as GCPs in follow-on surveys. When surveying beaches, often these fixed points will only be available on the periphery of the area of interest; therefore, multiple other GCP will be needed along the beach. Limiting the survey pattern to not include the surf zone and lagoon will decrease the survey time and extend battery life which can be used to decrease line spacing.

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VII. CONCLUSION

The seasonal manual breaching of the southern portion of the Carmel River State Beach is neither a necessary or a cost-effective method in the reduction risk of ephemeral river flooding in the vicinity of the lagoon during the winter season when increased precipitation and wave overwashing cause lagoon water levels to rise. The sediment transport from the breach was insufficient to keep the breach open and did not help to prevent future ocean to lagoon water transport. Secondary natural breaching of the looser sand resulted in rapid outflow with increased sediment transport onto the northern beach, significantly increasing the elevation to hinder wave overwash. Future studies should focus on the long-term effects of this sediment buildup to determine its exact effects on beach migration and lagoon area reduction.

Although GPCs were needed to reach sub meter accuracy in my experiment, this requirement was only due to the limited accuracy of the onboard UAV GPS. Centimeter accurate UAV GPS already exist and could be employed to remove the need for a person on the ground, allowing for autonomous surveys of remote, inaccessible, or hostile beaches. By comparing the hydrographic data to the DEM elevation data over the lagoon it was determined that the SfM measurements, even in shallower water, were inaccurate due to reflection/refraction and even more so in a river with substantial flow where invariable keypoints would be hard to identify. Therefore, this method is not very useful in determining development of sandbars that are still submerged which may present hazards to riverine forces, but it still provides an effective, rapid assessment tool for amphibious forces to determine changes to beach slopes and width in planning landing operations and follow on logistics over-the-beach.

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LIST OF REFERENCES

Baldock, T.E., F. Weir, M. G H ughes, 2007: Morphological evolution of a coastal lagoon entrance during swash overwash. *Geomorphology*, **95**, 398–411.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, and E. Twohy, 2009: Characterization of time and spatial scales of a migrating rivermouth. *Geophysical Research Letters*, **36,** L09402.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, and E. Twohy, 2013: Episodic closure of the tidal inlet at the mouth of the Russian River - A small bar-built estuary in California. *Geomorphology*, **189,** 66–80.

Carrivick, Jl, Smith, Mw, Quincey, Dj and Carver, Sj., 2013: Developments in budget remote sensing for the geosciences. *Geology Today*, **29 (4)**, 138–143.

Davidson, M. A., B. D. Morris, and I. L. Turner, 2008: A simple numerical model for inlet sedimentation at intermittently open-closed coastal lagoons. *Continental Shelf Res.*, **29,** 1975–1982.

FitzGerald, D.A., 1996: Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. *Journal of Coastal Research,* **23**, 47–71.

Hartley, R. I., and A. Zisserman, 2004: *Multiple View Geometry*. Cambridge: Cambridge University Press.

Hicks, D.M., and D.L. Inman, 1987: Sediment dispersion from an ephemeral river delta on the central california coast. *Marine Geology*, **77**, 305–318.

James, G. W., 2005: Surface Water Dynamics at the Carmel River Lagoon Water Years 1991 Through 2005. Monterey Peninsula Water Management District Technical Memorandum 05–01, 20pp.

Jimenez, J., A. H. Sallenger, and L. Fauver, 2007: Sediment transport and barrier island changes during massive overwash events. *Coastal Engineering 2006*, 2870–2879.

Johnson, K., et al., 2014. Rapid mapping of ultrafine fault zone topography with structure from motion. *Geosphere,* **10 (5)**, 969–986

Kraus, N. C., and S. Munger, 2008: Barrier beach breaching from the lagoon side, with reference to Northern California. *Shore & Beach*, **76,** 33–43.

Kraus, N.C., and T.V. Wamsley, 2003: *Coastal Barrier Breaching, Part 1: Overview of Breaching Processes, (ERDC/CHL CHETN-IV-56)*. U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Kraus, N. C., A. Militello, and G. Todoroff, 2002: Barrier Breaching Processes and Barrier Spit Breach, Stone Lagoon, California. *Shore & Beach*, **70**.

Laudier, N. A., E. B. Thornton, and J. MacMahan, 2011: Measured and molded wave overtopping on a natural beach. *Coastal Engineering*, **58,** 815–825.

Lowe, D.G., 2004: Distinctive Image Features from Scale-Invariant Keypoints. *International Journal of Computer Vision*, **60 (2)**, 91–110

National Oceanic and Atmospheric Administrations's National Buoy Data Center, 2018: Station 46239 (Big Sur Buoy). Acessed 04 May 2018, https://www.ndbc.noaa.gov.

Pierce, J. W.,1970: Tidal Inlets and Washover Fans. *The Journal of Geology*, **78 (2)**, 230–234.

Pollefeys, M., and L. Van Gool, 2002: From images to 3D models: How computers can automatically build realistic 3D models from images acquired with a hand-held camera. *Communications of the ACM*, **45 (7)**, 50–55.

Ralston, D.K., W.R. Geyer, and J.C. Warner, 2012: Bathymetric controls on sediment transport in the Hudson River estuary: Lateral asymmetry and frontal trapping. *Journal of Geophysical Research*, **117**, C10013

Richardson, John, 2017: *The Future Navy*. Chief of Naval Operations. United States Navy.

Sallenger, A.H,, R.A. Holman, and W.A. Birkemeier, 1985: Storm-induced response of a nearshore-bar system. *Marine Geology*, **64 (3)**, 237–257.

Scooler, Jeffrey, 2017: Episodic changes in lagoon water levels due to ephemeral river breaching and closure events. M.S. Thesis, Dept of Oceanography, Naval Postgraduate School, 47pp.

Smith, M., et al., 2014: Reconstructing flash flood magnitudes using 'Structure-from-Motion': A rapid assessment tool. *Journal of Hydrology*, **519**, 1914–1927.

Snavely, N., S.M. Seitz, and R. Szeliski, 2008: Modeling the world from Internet photo collections. *International Journal of Computer Vision*, **80 (2),** 189–210.

Westoby, M.J., et al., 2012: 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, **179,** 300–314.

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