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Applicability of CoastSnap, a Crowd-Sourced Coastal Monitoring Approach for US Army Corps of Engineers District Use

Ian Conery, Brittany Bruder, Connor Geis, Jessamin Straub,
Nicholas Spore, and Katherine Brodie

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Applicability of CoastSnap, a Crowd-Sourced Coastal Imagery Application for US Army Corps of Engineers District Use

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Abstract

This US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, technical report details the pilot deployment, accuracy evaluation, and best practices of the citizen-science, coastal-image monitoring program CoastSnap. Despite the need for regular observational data, many coastlines are monitored infrequently due to cost and personnel, and this cell phone-image-based approach represents a new potential data source to districts in addition to providing an outreach opportunity for the public. Requiring minimal hardware and signage, the system is simple to install but requires user-image processing. Analysis shows the CoastSnap-derived shorelines compare well to real-time kinematic and lidar-derived shorelines during low-to-moderate wave conditions (root mean square errors [RMSEs] <10 m). During high-wave conditions, errors are higher (RMSE up to 18 m) but are improved when incorporating wave run-up. Beyond shoreline quantification, images provide other qualitative information such as storm-impact characteristics and timing of the formation of beach scarps. Ultimately, the citizen-science tool is a viable low-cost option to districts for monitoring shorelines and tracking the evolution of coastal projects such as beach nourishments.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE), Coastal and Ocean Data Systems Research and Development Program, under Funding Account Code U4381344 and AMSCO Code 190012. The USACE Coastal and Ocean Data Systems Research and Development Program technical director at the time of publication of this report was Dr. Julie D. Rosati.

The work was performed by Coastal Observation Analysis Branch of the Flood and Coastal Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Ms. Erin Diurba was chief of the Coastal Observation Analysis Branch, and Ms. Lauren Dunkin was acting chief of the Flood and Storm Protection Division. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty V. Wamsley.

COL Christian Patterson was the commander of ERDC, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

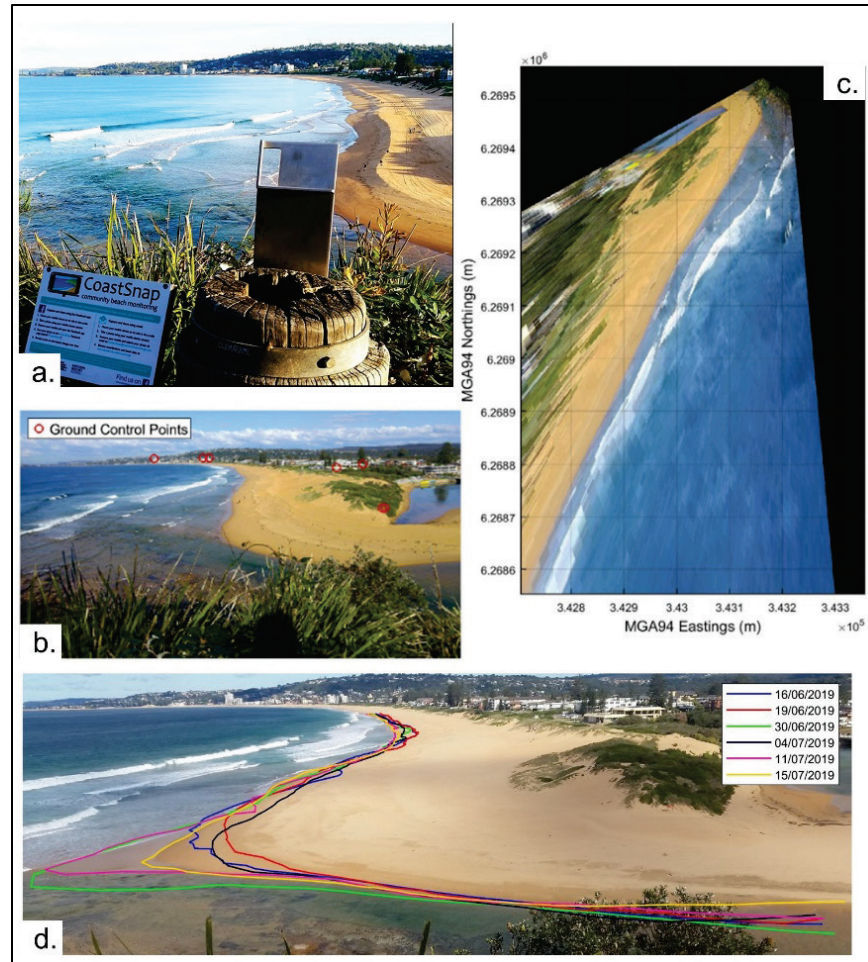
Shorelines along open coastlines evolve at a variety of time scales ranging from short (storm) to seasonal (months), annual, and decadal scales. To capture complex shoreline dynamics, extensive monitoring is necessary both in space and time. Despite the need for regular observational data, the costs and logistics of regular and long-term coastal monitoring efforts using conventional in situ survey and established remote sensing techniques can be cost and personnel prohibitive for US Army Corps of Engineers (USACE) districts, often resulting in the lack of data-driven planning.

Quantitative coastal imaging has been demonstrated to provide useful, low-cost observations of the evolution of coastal project sites (Bruder et al. 2019a; Bruder et al. 2019b; Onnink 2020). Using photogrammetry, traditional oblique imagery (i.e., Figure 1a) can be transformed into map coordinates with real-world length scales in georectifications (i.e., Figure 1b) with a suite of camera-calibration parameters. Once rectified, engineering-relevant information can be extracted out of the imagery, including shoreline position, sandbar position, nearshore bathymetry, and surface currents. A number of algorithms have been developed across the community, many of which are openly accessible through the Coastal Imaging Research Network (CIRN), (see Palmsten and Brodie [2022] for a review).

Coastal imagery can be collected via a variety of modalities, including dedicated high-accuracy coastal imaging stations (e.g., Holman and Stanley 2007; Bruder et al. 2019b), drones (e.g., Brodie et al. 2019), satellites (Luijendijk et al. 2018; Vos et al. 2019), and action cameras (Drummond et al. 2022). Each collection modality is suited to different-use cases with different accuracies and product libraries. For example, dedicated coastal imaging stations provide precisely calibrated collection platforms and a range of product suites, but they require access to electricity and communications, protection from the elements in harsh coastal environments, and can have significant setup and maintenance costs (greater than \$20,000). In addition, processing codes and creating metadata and data storage frameworks require subject matter experts

(SMEs). Collectively, these factors can make the use of fixed coastal imaging stations challenging and cost prohibitive for some use cases.

Figure 1. (a) Example University of New South Wales (UNSW) CoastSnap Station and corresponding; (b) example oblique image; (c) example rectified image; and (d) shoreline analysis. Image adapted from Harley et al. (2019).



A potential low-cost coastal monitoring strategy is CoastSnap, a global citizen-science project, developed by researchers at the University of New South Wales (UNSW), which aims to measure and quantify shoreline change using crowd-sourced cellphone imagery (Harley et al. 2019). CoastSnap relies on repeat cell phone oblique snapshots taken at the same location (Figure 1a) and collocated via social media or email to a centralized data server. Then, using an open-source MATLAB graphical user interface (GUI), each image can be calibrated using surveyed ground control points (GCPs) (Figure 1b), georectified images (Figure 1c), and shoreline analysis (Figure 1d) to observe shoreline change in real-world units (meters). The crowd-sourced imagery provides a frequent and low-

cost data source that has the potential to aid coastal managers, planners, and engineers and better document, communicate, and understand shoreline dynamics and drivers of change on both a local and regional scale. Furthermore, CoastSnap presents the opportunity for outreach and engagement with the community to promote understanding of beach dynamics and projects.

Harley et al. (2019) have developed a suite of MATLAB codes to facilitate the creation and data processing of CoastSnap stations that include templates for a fixed mount and signage (<https://github.com/Coastal-Imaging-Research-Network/CoastSnap-Toolbox>). The software provides a GUI for camera calibration and metadata organization, reducing SME requirements. As a result, stations have grown rapidly. CoastSnap first launched in 2017 with stations in Manly and Narrabeen (Australia). CoastSnap has expanded rapidly since then to an estimated 135 stations in 16 countries. The US Army Engineer Research and Development Center (ERDC) Jennette's Pier pilot represented the first US station.

1.2 Objective

As ERDC installed more CoastSnap stations, districts began to express interest. Particularly, districts were interested in the scale and accuracy of shoreline change that could be resolved as well as the personnel and resource requirements for installation and processing and outreach opportunities. To answer these questions, ERDC documented installation and data processing at a pilot US location. The primary objective of this study is to evaluate CoastSnap as a coastal monitoring tool for districts and identify best practices and lessons learned. This study uses the open-source CoastSnap software available on the CIRN github (<https://github.com/Coastal-Imaging-Research-Network/CoastSnap-Toolbox>) to process CoastSnap data. Ongoing research at ERDC will focus on integrating CoastSnap processing into ERDC's standard coastal imaging software suite.

1.3 Approach

To accomplish the objective and evaluate CoastSnap USACE-district feasibility, this study focused on the end to end set-up and operation of a CoastSnap station at a pilot US location, Jennette's Pier in Nags Head, North Carolina. The study aimed to evaluate practical considerations such as site selection, signage, needed software, and personnel demands learned from the installation. The data analysis portion of the work then

evaluated CoastSnap short (daily) and long (seasonal) term shoreline change accuracy at the site via comparisons with real-time kinematic Global Positioning System (RTK-GPS) walking and terrestrial mobile lidar surveys respectively. Lessons learned from practical and technical evaluations will then be used to surmise best practices and expected data product fidelity and accuracy for district applications.

1.4 Report Layout

The presented report will outline the installation of a CoastSnap Station at Jennette's Pier, North Carolina. Chapter 2 will briefly outline CoastSnap methodology; Chapter 3 will document the partialities of hardware installation at Jennette's Pier; and Chapter 4 will perform the technical assessment on the data. The report will conclude with listed best practices for CoastSnap installation, operation, and expected data fidelity.

2 CoastSnap General Setup and Procedures

2.1 Installation

CoastSnap utilizes a simple and low-cost camera mount (Figure 1a and Figure 4a) that is installed overlooking a coastal region of interest and used to constrain camera calibration parameters, particularly the extrinsics (i.e., camera position and orientation). Stations are ideally located in an area of high foot traffic at locations that are open year around as to not have seasonal data gaps. Field of view is important when considering locations, and looking along the coast is preferred as it maximizes potential data capture and impact of the station. In addition, high vantage points provide a more extensive camera view of the coastline and more potential GCPs. On the US East Coast, piers often provide the most elevated and alongshore oriented views of the coastline.

2.2 Calibration

The CoastSnap software performs camera calibration on each cellphone oblique image by relating the image coordinates (in pixels) of fixed GCPs in the image to real-world coordinates (i.e., State Plane, feet or meters, etc.). Knowing this information, the software solves for the camera position, orientation, and focal length of each image. This will be unique for each image due to variations in camera models and slight position offsets. Thus, GCPs need to always be present whenever an image is taken. (i.e., permanent fixed objects; Figure 1b). To constrain the nonlinear solution process, an initial estimation is provided of the camera position and orientation. To obtain this information, various points are required to be surveyed during installation in the desired coordinate system.

When choosing GCPs it is important to have a distribution across the image to constrain the solution; it is particularly problematic if GCPs appear in a single line. This is a challenge for CoastSnap stations, which required permanent GCPs. On many coastlines, fixed structures often exist behind the dune line and are not dispersed across the beach and into the water (Figure 1b).

2.3 Data Analysis and Workflow

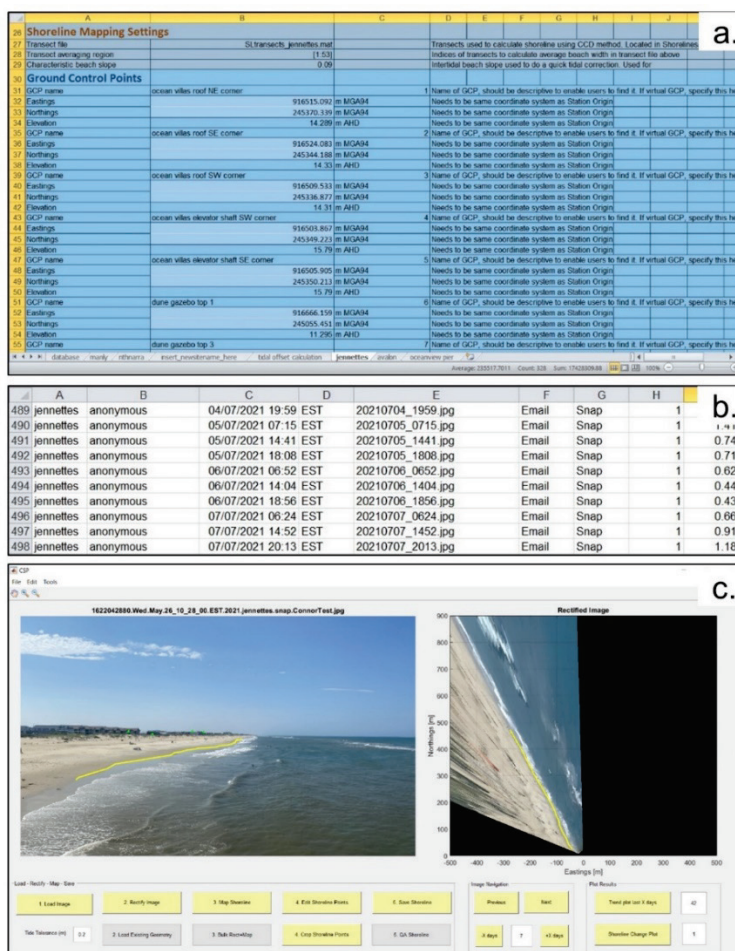
The following sections describe the workflow of the CoastSnap GUI, including the collection, ingestion and processing of imagery. Note that

while the CoastSnap software package aims to reduce SME via the GUI, it does still require a MATLAB license and some programming knowledge to run. The details of the workflow described here are highlighted to help USACE districts optimize implementation of the technology. More detailed information about the standard work flow can be found at <https://github.com/Coastal-Imaging-Research-Network/CoastSnap-Toolbox>.

2.4 Database Creation

For each station, the user needs to populate a Microsoft Excel spreadsheet template, included in the GUI and referred to as the Excel Database (Figure 2a and Figure 2b). The spreadsheet will include entries for each image as well as crucial information for rectification and shoreline identification parameters such as camera calibration initial estimations and GCP coordinates and combinations.

Figure 2. CoastSnap station information in (a) database, (b) image list in database, and (c) example output from graphical user interface (GUI).



The spreadsheet also includes file directories for crucial .mat files such as transect definition and tidal elevation time series in the coordinate system consistent with camera calibration and rectification. These files need to be created in MATLAB prior to running. Transect files define cross-shore transects in the desired coordinate system where shoreline estimates are extracted from the imagery, and tidal elevation files are .mat files with time-stamped estimates and measurements of tidal elevations at that site for accurate rectification. In addition to tidal elevation, wave parameters can be entered for average run-up elevation to further improve rectification. The database provides one entry for beach slope, significant wave height, and wave period to estimate a constant run-up value using Stockdon et al. (2006).

For many district project sites, water-level predictions and measurements can be found at National Oceanic and Atmospheric Administration (NOAA) Tides and Currents (<https://tidesandcurrents.noaa.gov/>), and wave measurements can be found at National Bouy Data Center (<https://www.ndbc.noaa.gov/>), and hindcast modeled at a higher resolution at US Wave Information Study (<https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00071>). Beach slope is estimated by previous surveys. For the Jennette's Pier pilot study, researchers combined a variety of water-level and run-up estimates and measurements to assess rectification accuracy, which will be discussed and detailed in the next chapter.

2.5 Data Collection

In addition to database creation, users are also required to create a data folder structure consistent with CoastSnap protocol (Harley et al. 2019) for each station where raw obliques can be culled, downloaded, and processed. Originally, submission avenues were either by email or social media posts with a specified address or hashtag on the CoastSnap signage, respectively. Then, USACE researchers download imagery manually from email or social media platforms, put images in appropriate local raw imagery folder as prescribed by the software and enter corresponding information into the same Excel database, including file name, station name, name of submitter (will be kept anonymous), date, time, image name, submission method, and quality of image (Figure 2b).

2.6 Data Processing

Once imagery is culled from the different sources, saved in the correct data folder, and an Excel database template is created, processing can begin through the MATLAB CoastSnap GUI. Users must have an active MATLAB license and the Signal Processing Toolbox as well as ensure MATLAB can correctly interact with Microsoft Excel files. First, a script is run to rename all unprocessed oblique images according to Argus naming convention and GMT timestamp as per database specification. Next, the user opens the CoastSnap GUI and selects Load Image where the software will automatically find all unrectified oblique images and load the first one. Once loaded, the user selects Rectify Image, which opens a cursor for GCP selection within the viewer based on the GCP combination to use within the Excel database. Due to the large spatial extent of the image, zooming in is required for precise GCP clicking. Then the software calibrates and rectifies the image, saving it as a .jpg format image.

Next, by clicking Map Shoreline, the CoastSnap algorithm automatically digitizes the instantaneous shoreline at cross-shore transects specified by the transect file (Harley et al. 2019). This is performed using an edge-detection technique that uses the *red* (sand) and *blue* (water) color channels along this transect in the georectified image. This method essentially locates the wet-dry boundary between wet pixels from the ocean and dry sand pixels from the beach, consistent with Boak and Turner (2005). If editing is required, the user selects Edit Shoreline Points, which enables the dragging and deleting of shoreline vertices. In ERDC's experience, it is estimated that 1 in 5 to 10 shorelines required minor editing lasting generally less than 30 sec.¹ Then, the shorelines are georectified into real-world coordinates using the tracked shoreline image coordinates, camera calibrations, and water-level estimates. Last, the shoreline can be saved to a .mat file for each image by selecting Save Shoreline. There are additional plotting functions available within the GUI including trend and shoreline-change plots based on specified time ranges.

Overall, the time required to run all the aforementioned processing steps takes approximately 1–2 min per photo entry. The longest step is setting up the database, particularly if one does not have knowledge to enter tidal

¹ For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–7, respectively. <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

and transect information in MATLAB format and ensure the current version is compatible with Microsoft Excel.

2.7 Implications of Instantaneous Shoreline Measurements

Note that CoastSnap uses image snapshots where it measures the instantaneous shoreline; this is often the leading edge of the thin layer of water between swash events as water infiltrates into the beach (e.g., Figure 2c). This is not a datum-based shoreline such as mean water level and has implications in the resultant data.

First, the measured instantaneous shoreline position will vary as a function of water level elevations due to time-varying tides, wave- and wind-induced setup, and run-up. Thus, an image taken at maximum run-up (swash uprush) 10 sec after an image is taken at minimum run-up (swash rundown) will provide different cross-shore shoreline positions. This is similarly true for images taken at low tide versus high tide, or low-wave conditions versus high-wave conditions. Ultimately, CoastSnap is not tracking a constant elevation contour in time, which introduces noise in any time record or shoreline measurements. The size of this noise is site dependent and is a function of tidal range, wave variability, and beach slope.

The second implication of snapshot-derived shoreline measurements is rectification accuracy. For accurate horizontal rectification (easting and northing), a correct elevation of the shoreline needs to be provided. While this can be done with time-averaged imagery and tidal level with relative accuracy, wave effects and phase-resolving wave effects are much more difficult to incorporate. CoastSnap incorporates tidal predictions and average run-up estimates for a location into the georectification process but does not account for time-varying run-up elevations. This affects data accuracy as well as noise.

Harley et al. (2019) used a smoothing-spline interpolation of temporally varying shoreline positions to reduce noise associated with water-level oscillations and georectification errors. The effect of both snapshot derived shoreline implications will be investigated in Chapter 4.

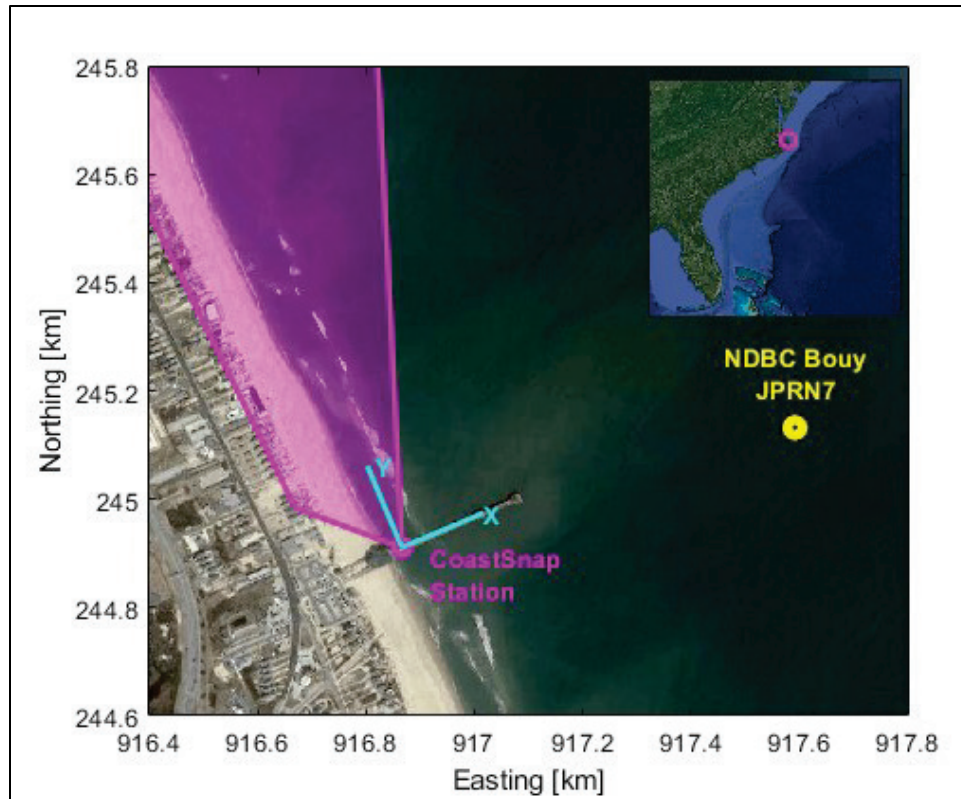
3 Pilot Installation: Jennette's Pier, Nags Head, North Carolina

3.1 Location

Jennette's Pier is a state-of-the-art concrete pier extending 1000 ft (304 m) into the Atlantic Ocean in Nags Head, North Carolina; part of the Northern Outer Banks (Figure 3). Originally constructed in 1939, the pier was revitalized after impacts from Hurricane Isabel in 2003. Part of the North Carolina Aquarium System, the pier hosts educational programs and camps covering a range of topics including angling, surfing, marine biology, coastal dynamics, etc. Jennette's Pier is open year round and welcomes thousands of visitors annually, primarily for angling and sightseeing. Part of the pier's mission is promoting environmental conservation through a variety of programs. Aligning with the goals of the environmental educational center, Jennette's Pier was excited to host the first US CoastSnap installation after ERDC researchers proposed the idea, explaining both the system and potential benefits of coastal monitoring and community outreach. While a formal agreement was not needed for this installation, it is possible many locations may require a right of entry or similar agreement, which can be arranged via district's legal departments.

In addition to its civic advantages (educational mission, foot traffic, etc.), the location is advantageous for a data-quality aspect as well. The vantage point from the pier provides long, unobstructed views of the shoreline (Figure 3, *pink area*; Figure 4b) due to its elevation above the beach. As will be discussed in the data assessment section (Chapter 4), increased elevation also helps increase accuracy of the CoastSnap shoreline estimate (Harley et al. 2019). In addition to limited obstructions, the site is advantageous due to the many fixed objects in the field of view (FOV) (e.g., beachfront houses) to serve as GCPs as will be discussed in the calibration section (Section 3.3).

Figure 3. Location of pilot US Army Engineer Research and Development Center (ERDC) CoastSnap installation: Jennette's Pier, Nags Head, North Carolina. *Pink-shaded area* represents field of view (FOV) of camera. *Light-blue lines* represent rotated local coordinate system.



3.2 Pilot Installation

To ensure durability amid prolonged exposure to the elements, the mount was custom fabricated with stainless steel. Stickers to the mount were added (Figure 4a) to attract visual interest (“try me”) with an accompanying phone logo and arrows. A “press phone to plate” sticker was added with the intention of preventing some users from leaning their cell phone at an inconsistent angle. Screws were bolted through the wooden railing, and the mount was adjusted to the desired roll, pitch, and yaw; then the position was locked into place with an extra keeper bolt (Figure 4a).

At Jennette’s Pier, the particular location of the camera mount was selected in coordination with the pier staff based on several factors, including proximity to foot traffic, consideration for benches and weddings and events. The research team considered these host concerns along with view-angle requirements for data-quality purposes. The angle was chosen

to maximize shoreline view (considering extents of high and low tide) as well as maximum distribution of potential fixed points for GCPs across the image (in the case of Figure 4a, beachfront structures). This distribution is crucial for accurate camera calibration.

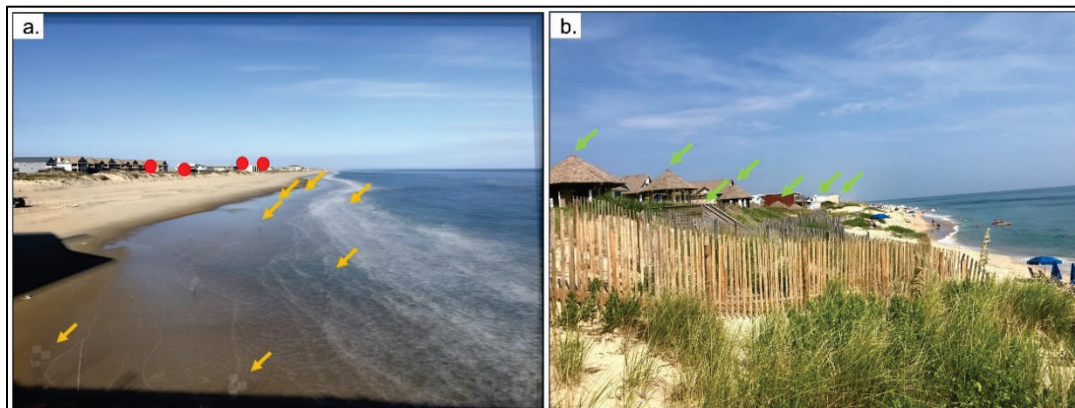
Figure 4. (a) Photograph of CoastSnap mount and (b) example image taken from mount.



3.3 Pilot Calibration

Using a high-precision RTK-GPS, researchers collected an abundance of GCPs from fixed structures that had sufficient contrast from their background and were dispersed across the field of view of the camera to provide multiple GCP combinations for image rectification. GCPs included beach walkover railings, deck corners, gazebo tops, hotel roof corners, and elevator shafts (Figure 5a,b; *green arrows* and *dots*;). In addition, the camera mount itself was surveyed for the solution initial guess.

Figure 5. (a) Composite CoastSnap image with on land ground control points (GCPs) (*red dots*) and in water GCPs (*orange arrows*); (b) field photo showing other collected GCPs (*green arrows*) collected and used in finding optimal image rectification.



Similar to many coastlines, at Jennette's Pier fixed structures exist behind the dune line and are not dispersed across the beach and into the water (Figure 5a; *red dots*). As a result, many calibration solutions were incorrect. To improve subsequent calibrations, a more precise initial calibration process was required. The team attached a small checkerboard target to the RTK-GPS pole, measured the offset to the antenna, and a team member waded into the water with it. The team member surveyed various points while another captured photos from the station using the same camera and capture setting (Figure 5a; *orange arrows*). This collection of photos was combined into a stabilized composite image in the MATLAB Image Processing Toolbox for a better distribution of GCPs across the image. Camera position and orientation of this image were solved for using the GCP survey values (with the correct antenna offset) and using a modified version of the CIRN Introduction to Coastal Imaging Toolbox (Bruder and Brodie 2020), which solved for camera position, pose, and focal length only (outside of the CoastSnap GUI). This provided a more precise initial camera position and initial pose for future CoastSnap GUI calibrations.

For future efforts, the team also determined more fixed GCPs could be extracted at similar precision (approximately 5 cm error) using terrestrial lidar measurements. Mounted on top of a van (Conery et al. 2019), the laser reaches approximately 1 km and captures fixed structures not accessible by foot with RTK-GPS. This also reduces time and resources needed to ask private property owners permission for access onto their property.

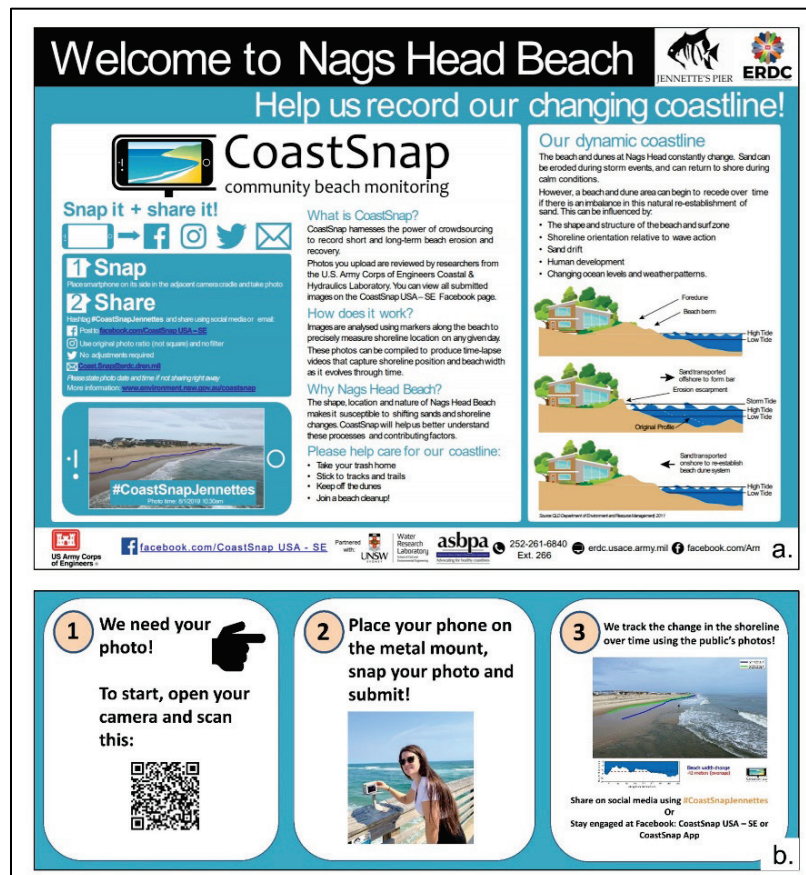
3.4 Pilot Signage and Interaction Design

The cellphone-camera cradle is accompanied by signage detailing instructions for sharing participants' images. The original Jennette's Pier CoastSnap sign was designed off a template from UNSW (Figure 6a). The *left panel* included instructions and options on how to submit photos through email or other social media. The *center column* of the sign displays info about CoastSnap (e.g., how it works). Last, the *right-hand side* provides some information on coastal dynamics and what processes may be influencing the site from a shoreline change perspective. If interested in more information, users can follow links to the website and social media. An ERDC email (coast.snap@erdc.dren.mil) was created to field submissions for users that prefer email. A Facebook page (CoastSnap USA–SE) was created to communicate findings and engage with the

public, where *SE* represents southeast. This regional naming was established to accommodate other stations in the region and future sites. The research team felt a regional page would be more interesting to users than a single page per site, in addition to having more potential content to choose from for public posts.

As mentioned previously, users submitted through email or social media. However, submissions were lower than expected, so the research team observed and interviewed several participants and learned that users were reluctant at times to take a photo and invest the time to read instructions and open email or social media. This motivated the team to simplify and streamline the submission process. Part of this effort aimed at reducing the text and instructions on the sign in addition to altering the placement of the modified sign (Figure 6b). The added sign panel was placed on the rail immediately next to the mount to ensure a clear connection to the camera mount for users (Figure 2a). At the recommendation of the Jennette's Pier education staff, the instructions were presented in a horizontal 1–2–3 method to attempt to limit confusion.

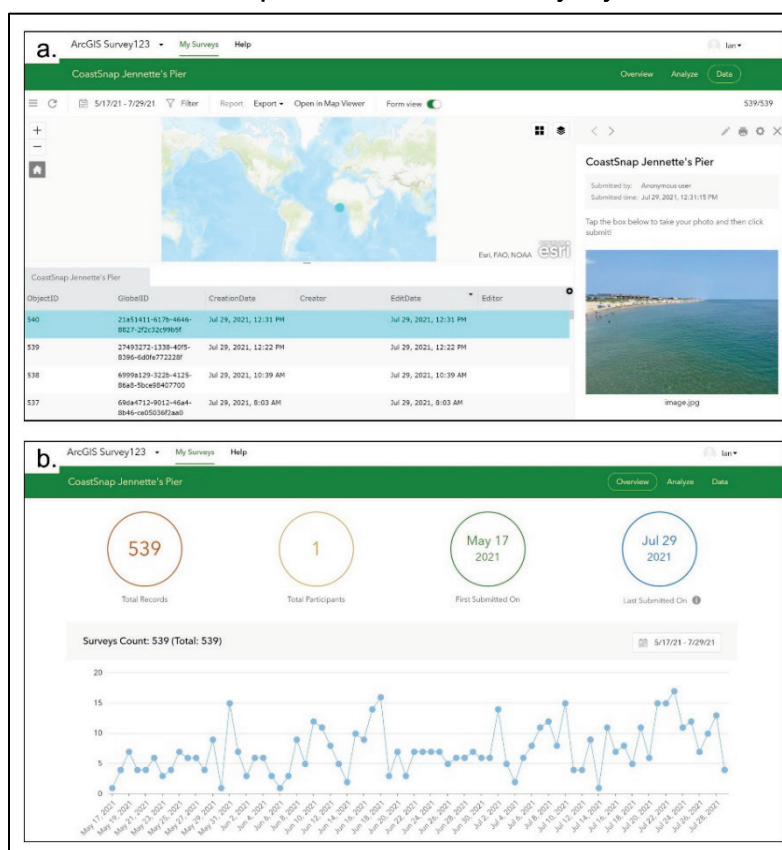
Figure 6. (a) Original example CoastSnap signage and (b) new signage.



The other facet of this effort was to have submission via a quick-response (QR) code and ArcGIS Survey123 Platform (Figure 7), currently supported by USACE through an Esri enterprise license. First, citizen scientists are prompted to scan a QR code, which opens an ArcGIS Online webpage on their smartphone. They are then instructed to place their cell phone in the metal bracket and take a snapshot image that is automatically submitted to a centralized user account on Survey123 where the imagery is also securely stored (Figure 7).

Imagery can be batch downloaded for processing in lieu of manually collecting from Twitter and email. It was determined a QR code for each CoastSnap station was ideal for organizing data. This modified submission process reduces the time commitment and confusion for submission and importantly guarantees a time stamp that was sometimes previously omitted through email and social media submission. Additionally, it centralizes the data and eliminates the previous data-culling effort from the previous submission method. Survey 123 also provides useful graphics to track submission numbers through time (Figure 7b).

Figure 7. (a) Survey123 site homepage containing site images and (b) example submission statistics by day.



After the implementations of the new signage and QR code modification, submissions increased drastically (June; Figure 12). Prior to the implementation of Survey123, eight CoastSnap images were submitted during July 2020, with an average of 0.26 submissions per day. The highest daily number of useable images submitted was 1. After the implementation of Survey123, 276 CoastSnap images were submitted during the month of July 2021. On average, 8.9 images were submitted per day during the month of July, and the highest number of CoastSnap images submitted on a single day was 17, which occurred on 23 July 2021.

The substantial increase in photo submissions allowed researchers to capture shoreline positions throughout the full tidal cycle most days. In particular, this makes the shoreline data more useful when comparing shoreline positions pre- and poststorm. Furthermore, more data help to reduce shoreline position noise and uncertainty associated with variable water levels between instantaneous shoreline estimates as will be shown in the data assessment section (Chapter 4).

3.5 Pilot Database Construction

An essential component of the database is the GCP location information and specified GCP combination the station operators have found to be the best rectification solution. For the Jennette's Pier example, the best solution was determined using four GCPs within the center of the frame (Figure 2a and Figure 5a) and initial guesses input in the database from the advanced calibration procedure.

3.6 Pilot Data Collection

As shown on the original signage (Figure 6a), citizen scientists at Jennette's Pier would take a photo and have the option of emailing it to the specific ERDC address or sharing through social media through the hashtag identifier #CoastSnapJennettes.

For Survey123 submissions, images were downloaded and input into the spreadsheet where name and time were assigned, requiring station operator interaction. A custom Python script is in development to batch download imagery and automatically assign a time stamp.

Data collected from this station during the pilot will be described and analyzed in the following chapter. In total, 1008 images were submitted

during the pilot time period, and 323 images were processed for analysis to save on processing time while still capturing high temporal-frequency shoreline movement.

4 Pilot Data Assessment

The following chapter will explore the accuracy of CoastSnap shoreline estimates by comparing estimates to walking RTK-GPS and mobile terrestrial lidar surveys. First, walking surveys are used to compare CoastSnap estimates during different tidal and wave conditions to assess the accuracy sensitivity to water level elevation error for a given image and instantaneous shoreline estimate. Second, the terrestrial lidar surveys are used to assess whether CoastSnap can accurately capture long-term shoreline change with uncertainty introduced by instantaneous shoreline measurements.

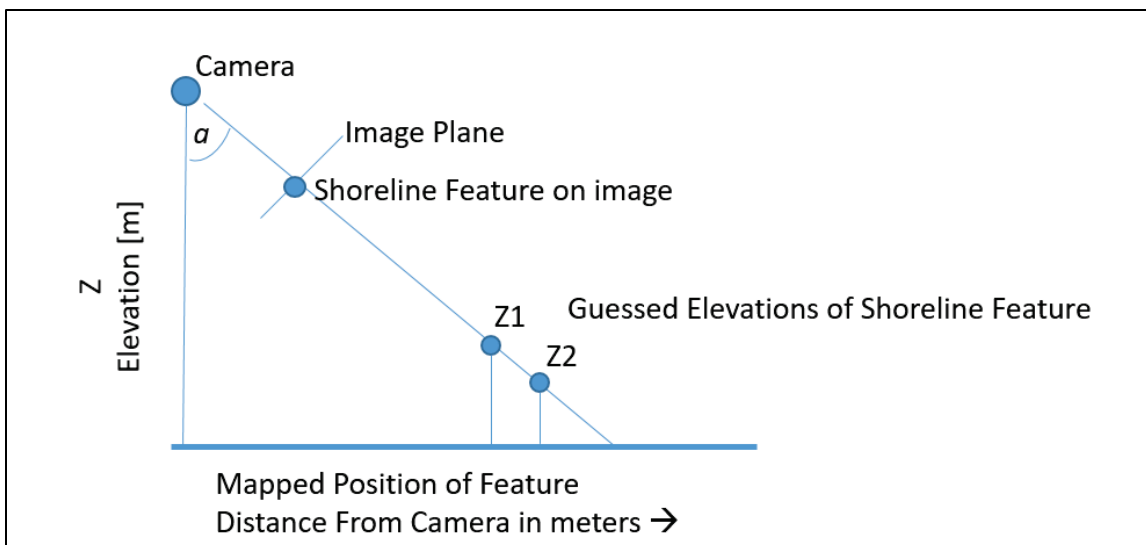
4.1 Shoreline Sensitivity to Run-Up and Tidal Elevations

When transforming a low-angle oblique image to a georectified image, the user needs to specify the elevation of each feature to accurately transform pixels to horizontal georeferenced coordinates. If the elevation of a feature is inaccurate, an incorrect horizontal translation of the feature will be introduced when the image is georectified (Figure 8). The larger the elevation error (e.g., difference between Z_1 and Z_2 in Figure 8a), the larger the lateral distance from the camera or error (Figure 8a). Also, the more oblique angle of the image (larger angle a), the larger the resultant lateral error (Figure 8b). As images become more nadir (smaller a), these type of errors become less significant. This is particularly problematic for CoastSnap installations because (1) CoastSnap images are snapshots and are actually mapping an elevation, which is an unknown combination of the instantaneous tide elevation, wave-driven water levels (run-up and rundown) and wind-driven water levels, and (2) this error is compounded by the fact CoastSnap FOVs are typically from low elevations such as piers and beach accesses that require oblique look angles and large a to cover large stretches of beach.

In fixed coastal-imaging stations from high platforms, typically the predicted tidal elevation is used. This is appropriate since cameras are from high platforms with more nadir look angles and typically statistical images (video averages) are taken to get more average shoreline positions. CoastSnap estimates shoreline elevation using a user-prescribed tidal time series, which can be predictions or measurements and a constant estimate of wave run-up using the Stockdon et al. (2006) equation with a station operator-provided average beach slope, wave period, and wave height. For

a given image, the tidal elevation and run-up value are summed for a shoreline elevation estimate.

Figure 8. Diagram emphasizing the effect of elevation error in georectifications.

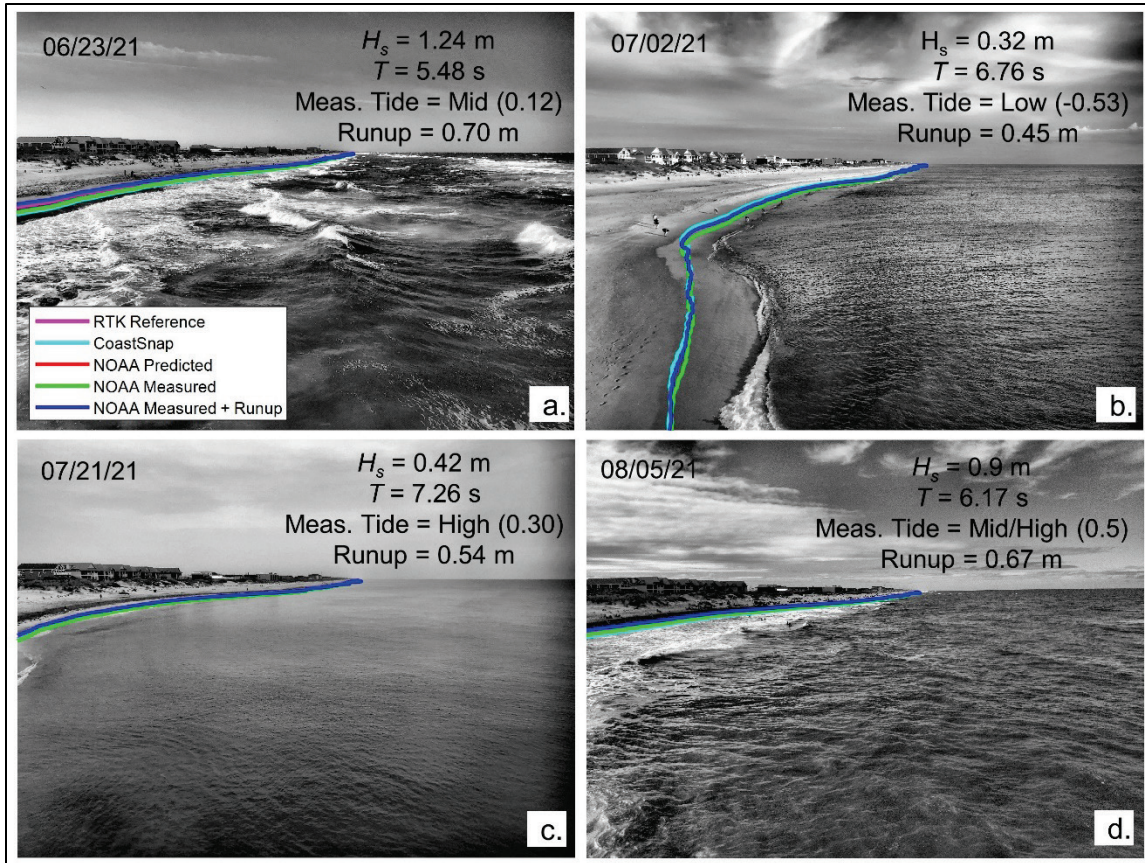


To explore the extent of this error, researchers conducted RTK-GPS walking surveys of the shoreline position (wet-dry boundary) during different tidal and wave conditions while simultaneously taking a CoastSnap image at Jennette's Pier (Figure 9). The four conditions were

- 06/23/21 with mid tide and large wave height (Figure 9a),
- 7/02/21 low tide with low wave height (Figure 9b),
- 7/21/21 high tide with low wave height (Figure 9c), and
- 08/05/21 mid tide with high wave height (Figure 9d).

Researchers then compared CoastSnap shoreline estimates in georectified space using various elevation estimates that would be available to districts: (a) NOAA Tidal Prediction + Average Run-Up Value (as per original CoastSnap), (b) NOAA Tide Prediction, (c) NOAA-measured tidal elevation, and (d) NOAA-measured tidal elevation and run-up estimates from time-varying wave parameters. For the Jennette's pilot, tidal predictions and measurements were taken from NOAA station 8651370, wave data from the Field Research Facility (FRF) 8 m array, and a constant beach slope of 0.1 from previous terrestrial lidar surveys. For use in CoastSnap, the calculated average wave height was 1.0 m with a period of 9 sec.

Figure 9. Example CoastSnap imagery taken during different wave and tidal conditions. The *pink line* is real-time kinematic Global Positional System (RTK-GPS) survey reprojected into image coordinates using individual camera calibrations. Note, the *pink* RTK-GPS line may not be visible in sections where overlap occurs from the other lines.



In Figure 9, the coordinates (easting, northing, and elevation) of the walking survey are projected into image space using the unique camera calibration calculated in CoastSnap for each image. Qualitatively, all estimates for all conditions match the walked RTK instantaneous shoreline well, suggesting a good camera-calibration solution for each image. In Figure 10, the RTK-GPS coordinates of the walking survey are plotted in a real-world, rotated local coordinate system as defined in Figure 3 where the origin is the CoastSnap camera cradle, Y is aligned with the northerly alongshore direction of the beach, and positive X is aligned with the offshore direction. To assess the effect of elevation error, the image coordinates of the GPS-RTK lines in Figure 9 are considered truth and are georectified into the real-world, rotated local coordinate system, using the camera calibrations and various elevation estimates. The elevation specified for each 2D point projected on the 3D surface (commonly referred to as UV) is held constant across the spatial domain in each image. The image coordinates of the walking survey were used in

lieu of the identified CoastSnap shoreline to remove any effect of the edge-detection algorithm and isolate errors due to incorrect elevation in the rectification process.

Figure 10. Original RTK-GPS walked shorelines (*magenta*) compared to CoastSnap shorelines georectified from image space using various elevation estimates available to districts.

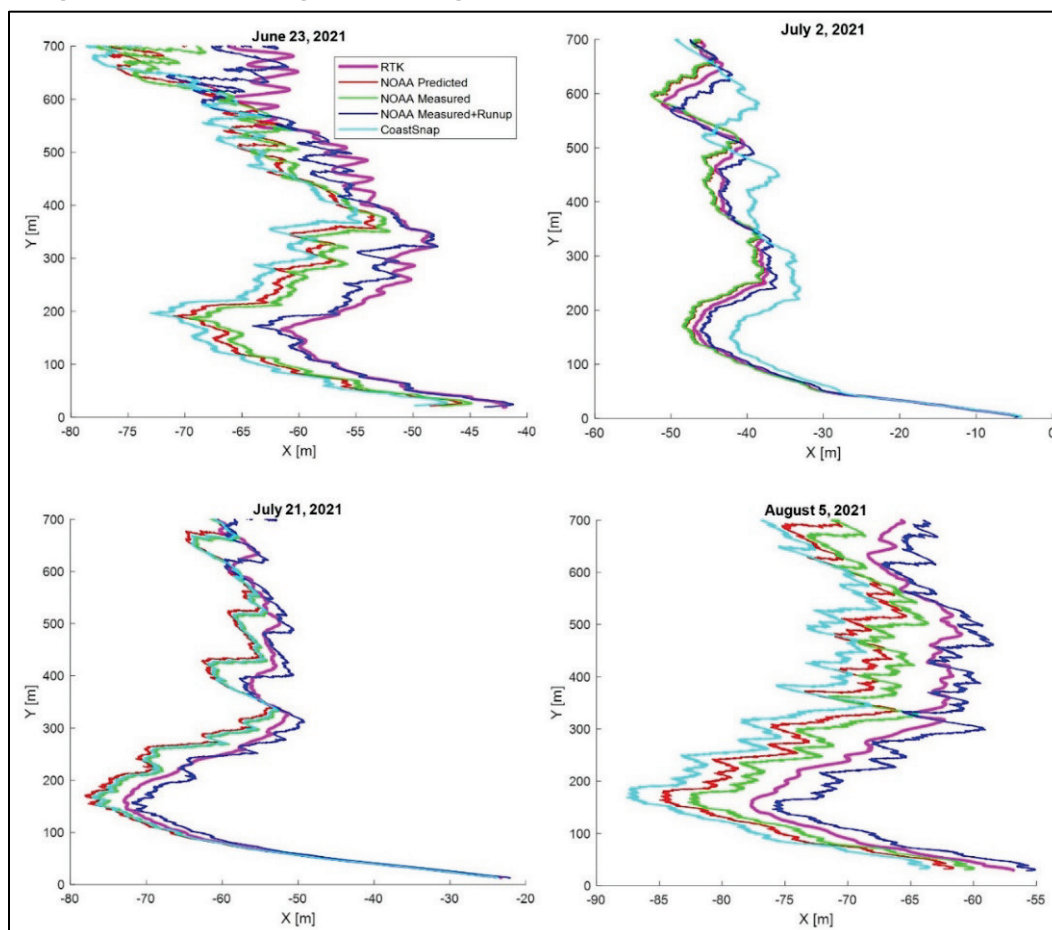


Figure 10 highlights the lateral spread of the shoreline estimates about the RTK-GPS survey, and Table 1 and Table 2 provide the calculated root mean square error (RMSE) and bias as compared to the RTK-GPS survey. All reprojected surveys appear noisier than the walked surveys; this is because a constant elevation is provided for each point as compared to the variable elevation of the walked survey along the beach. This is also the reason why the error is not in a consistent direction or magnitude along the beach. That is, if the elevation is variable due to beach cusps or other features, there will be different degrees and directions of error depending on the magnitude and sign of the elevation relative to the constant value. This error will be inherent to all estimates regardless of what elevation estimate used.

The largest RSME and bias occur on the days with the two larger wave events (23 June and 05 August), where shoreline error estimates are up to 17 m offshore of the RTK survey (Table 1). For both of these dates, the NOAA Measured + Variable Run-Up provides the best (smallest) root mean square deviation (RMSD) and bias (approximately 6 m and 3 m; 5 m and 3 m onshore) (Table 1). From there, error increased for CoastSnap, NOAA–predicted, and NOAA–measured with RSMDs and bias ranging from 4 to 18 m and 4 to 17 m offshore, respectively (Table 1 and Table 2). This emphasizes that for images taken on days with larger wave events, shoreline positions using the standard CoastSnap processing will have highest error. For the most accurate results during these conditions, shoreline elevation should be derived from measured tide and wave conditions for proper rectification.

Table 1. Root mean square error (RMSE) of RTK-GPS georectified shoreline estimates (meters). Colors are binned to represent RMSEs (<5 m, *green*; 5 to 10 m, *yellow*; 10 to 15 m, *orange*; 15 to 20 m, *red*).

—	6/23 (High Tide/High Wave)	7/02 (Low Tide/ Moderate Wave)	7/21 (Low Tide/ Low Wave)	8/05 (Mid Tide/ High Wave)
NOAA–Predicted	15.7143	1.58	4.67	6.96
NOAA–Predicted + Average Run-Up (CoastSnap)	18.5128	8.30	3.70	9.73
NOAA–Measured	13.7925	1.89	3.32	4.60
NOAA–Measured + Variable Run-Up	5.99	2.11	3.15	2.91

Table 2. Bias of RTK-GPS georectified shoreline estimates (meters). Negative values indicate offshore bias.

—	6/23 (High Tide/High Wave)	7/02 (Low Tide/ Moderate Wave)	7/21 (Low Tide/ Low Wave)	8/05 (Mid Tide/ High Wave)
NOAA–Predicted	–14.45	–1.36	–4.28	–6.74
NOAA–Predicted + Average Run-Up (CoastSnap)	–17.16	7.75	–3.28	–9.48
NOAA–Measured	–12.59	–1.6726	–2.87	–4.39
NOAA–Measured + Variable Run-Up	4.86	1.84	2.56	2.61

Ultimately, this analysis highlights when standard CoastSnap processing Based on Figure 8, if water level is overestimated (Z_2 as compared to Z_1), the object will be mapped closer to the camera; if water level is underestimated, it will be mapped farther away from the camera. This corresponds to more onshore or offshore depending on the relative camera angle to the shoreline. For the pilot installation where the camera is looking onshore, overpredictions of elevations provide a more offshore estimate, and underpredictions of elevations provide a more onshore estimate. Thus, if using measured or predicted tides without wave information, or underestimated wave information, the shoreline position will be projected more onshore than in reality for large wave events if the camera is located offshore of the beach (looking onshore). This trend would be reversed if the camera were located on the beach looking offshore.

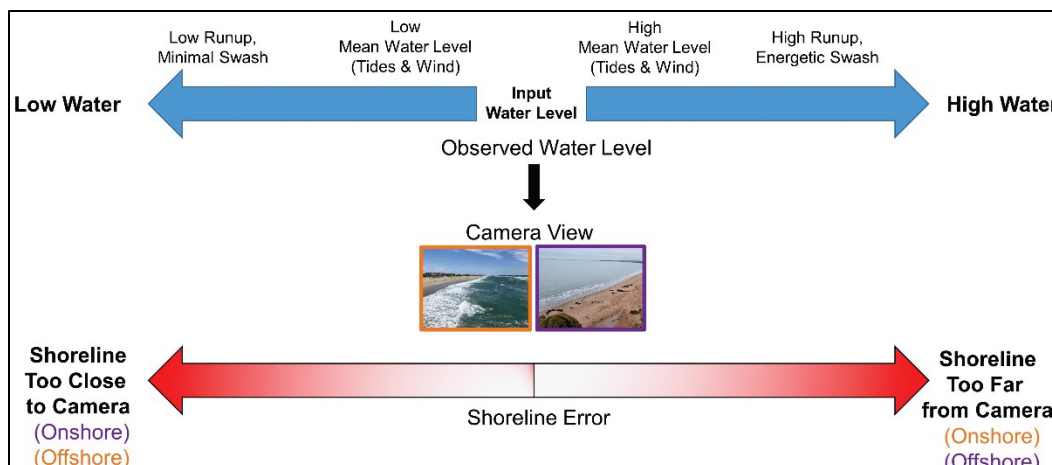
The smallest RMSE and bias estimates occur during the 02 July low-tide, low-wave event when using the NOAA-predicted and NOAA-measured water-level elevations, (RMSE, bias of approximately 1–2 m; Table 1). Thus, if little wave action at the shoreline is evident, most likely using the measured or predicted tide alone will provide best accuracies as any correction for wave run-up may introduce additional errors.

For the low-tide and low-wave event (21 July), there is less spread between the nonrun-up considering elevations and run-up elevations, all with RMSE within 3–5 m with offshore bias for run-up and onshore bias for nonrun-up elevations (Figure 1). Thus, it can be assumed there is some small runup (0.54 m) due to waves propagating to the shoreline without breaking as can be seen in Figure 9c, providing some error for both methods. NOAA predicted the largest RMSE near 4.5 m and bias of 4 m. This is due to the NOAA prediction underestimating elevation and providing a more onshore estimate. The NOAA measured water level plus Run-up provided the smallest RMSD and bias of 3.15 and 2.56 m respectively; however, CoastSnap estimates were only approximately 0.55 m worse offshore (Table 1). Thus, for conditions near average conditions, CoastSnap predictions provide nominal accuracy.

Ultimately, this analysis highlights when standard CoastSnap processing approaches will over- or underpredict shoreline position due to error in elevation estimates. A conceptual diagram synthesizing these relationships is provided in Figure 11 and described briefly in text here. Error estimates are largest during large wave events where there is significant run-up.

During these conditions, using measured water levels and estimated run-up from a nearby wave bouy can significantly reduce this error. If standard CoastSnap processing is used (predicted tides and average run-up), shoreline position will be biased onshore when the camera is located offshore looking onshore (Figure 11). If wave conditions are very small, it is best to simply use measured or predicted tide elevations without addition of wave run-up; otherwise, the shoreline position may be biased offshore when the camera is located offshore looking onshore (Figure 11). If waves are close to the average conditions and energy is still reaching the shoreline, both run-up and nonrun-up estimates have similarly small errors in shoreline position. Thus, recommended best practices are to use measured tidal elevations for CoastSnap rectifications except for imagery collected during large waves. In these conditions, it is best to either remove the images from the analysis or use wave information to estimate wave run-up and add it to the measured tide elevation. Note that winds may also influence local water levels, where strong onshore winds would result in higher water levels along the shoreline.

Figure 11. Conceptual diagram depicting the conditions affecting variable CoastSnap accuracies. Tides, winds, and waves are the dominant factors controlling water levels.



4.1.1 Shoreline Position Trends

The following section evaluates CoastSnap's ability to monitor long-term seasonal trends in shoreline position. Shorelines were tracked from 160 images from June 2020 to September 2021 using the standard CoastSnap GUI (with NOAA-predicted plus average run-up). This was a subset of the total submissions where only up to three images were used per day. If more than three images were available, an image closest to low tide, closest to high tide, and mid tide were selected. As mentioned in

Section 2.7, this approach aims to reduce the noise in the data. For this effort, the team determined it was not necessary to process more than 3 images daily, despite some days where submissions exceeded 15.

The cross-shore position of the shoreline at alongshore location $Y = 200$ m is plotted for each image in Figure 12 in *pink*. In *red*, the monthly average is plotted following the spline interpolation approach of Harley et al. (2019). This was compared with shoreline estimates from the FRF Coastal Lidar and Radar Imaging System (CLARIS) terrestrial lidar scans plotted in *blue*. CLARIS collects highly accurate 3D point clouds (<5 cm error), and more information on accuracies and concept of operations can be found in Spore et al. (2019) and Conery et al. (2020). Instead of tracking an elevation contour, unfiltered CLARIS point clouds were used to digitize the land-water interface generally within approximately 2 hr of low tide to be consistent with the CoastSnap shoreline definition. Figure 12 highlights CoastSnap can capture overall trends in shoreline evolution on seasonal timescales. Scatter in the CoastSnap shorelines due to tidal and wave conditions is evident with the increased submissions in summer 2021 with addition of the QR code. Estimates range between ± 20 m of the overall trend. Despite this noise introduced by instantaneous snapshot analysis, the monthly average captures the seasonal shoreline evolution quite well, demonstrating the potential usefulness in CoastSnap data for district coastal monitoring.

Figure 12. Cross-shore shoreline position calculated by standard CoastSnap at $Y = 200$ m processing as compared to terrestrial lidar shoreline surveys.

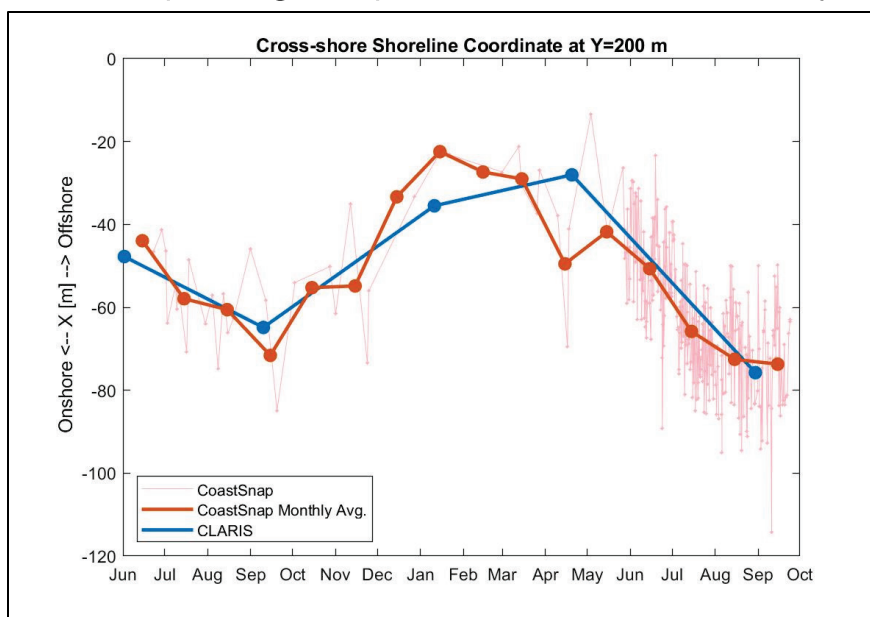
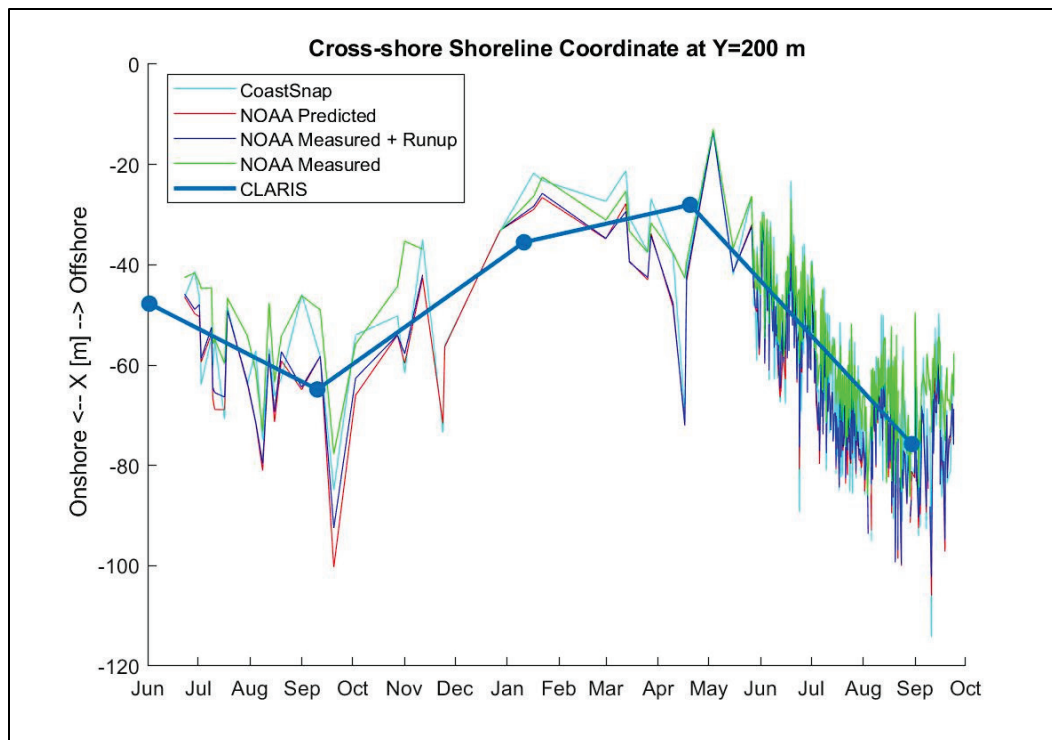


Figure 13 plots the CoastSnap shorelines at $Y = 200$ m using different water-level estimates as presented in Figure 10. Similar to Figure 11, tidal water levels were taken from NOAA time series, wave information from buoy data, and slope were considered constant at 0.1. While the different water-level estimates do provide different spread, accuracy, and variability for instantaneous estimates (particularly May 2021), they all highlight the same trend as the lidar surveys. Thus, if only considering overall trends as potential data products, errors from imprecise water level are not detrimental.

Overall, the results of the trend analysis comparing CoastSnap to a higher-fidelity, vetted measurement platform are quite encouraging for considering CoastSnap as a reliable quantitative tool. Furthermore, Figure 12 and Figure 13 highlight the valuable additional context provided by frequent image submissions; typical survey methods like mobile lidar are collected less often than images, and CoastSnap can serve to fill in data gaps between other traditional surveys.

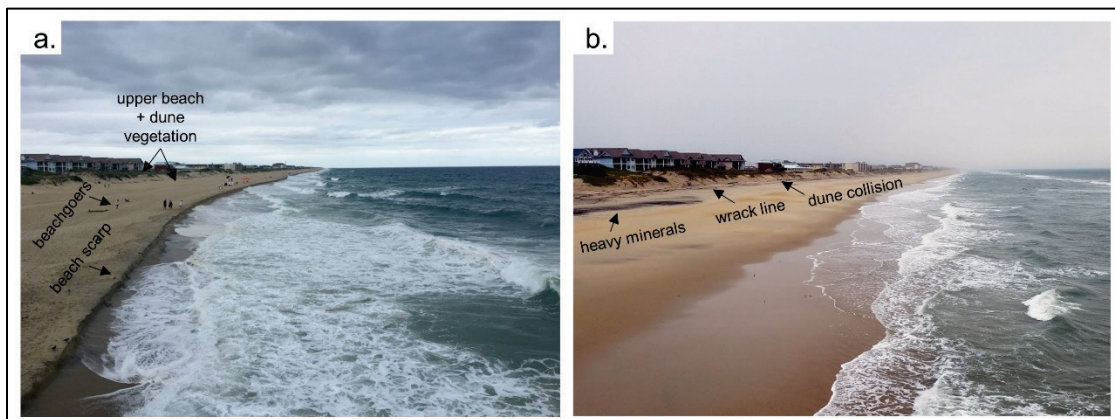
Figure 13. Cross-shore shoreline position calculated using CoastSnap with varying water-level estimates as compared to terrestrial lidar shoreline surveys.



4.1.2 Qualitative Data

Prior sections demonstrated the efficacy of extracting shorelines from citizen-science imagery, yet images also contain other potentially useful qualitative information for coastal managers. From a morphologic perspective, images can reveal the timing and extent of cusps and beach scarp formation (Figure 14a), which have important implications for beachgoers and safety-vehicle trafficability. As such, town managers could use the citizen-science imagery to help determine when to limit beach driving due to the presence of scarps. In addition, storm impacts can be elucidated by not only examining changes in beach width from imagery but also revealing collisional impacts to protective dunes and total water levels from wrack lines (Figure 14b). From a geologic perspective, images can reveal sediment characteristics such as the presence of heavy minerals or coarse-shell hash cover (Figure 14b). Imagery can also show changes in ecology (e.g., dune grass coverage, colonization of the upper beach in spring and summer), which can influence morphology (Figure 14a). Last, the number of beachgoers or vehicles, or both, can be estimated (Figure 14a).

Figure 14. Examples of qualitative information visible in cell-phone imagery.



5 Conclusions and Recommendations

5.1 District Applicability

CoastSnap pilot efforts have revealed several aspects of the citizen-science platform that would potentially make it useful for USACE districts. Perhaps most important, analysis showed that it is an accurate quantitative tool to measure changes in shoreline position over short- (daily) to long-term scales (multiyear). Many USACE beach project sites suffer from infrequent monitoring data due to high costs and required personnel with traditional survey means, and CoastSnap represents a significantly lower-cost data source that requires limited personnel and maintenance. In particular, these data show CoastSnap could be used to quantitatively track the monthly subaerial evolution of beach nourishments or shoreline, or both, evolution onshore of nearshore berm placements in addition to monthly to seasonal-scale natural evolution of the shoreline. The citizen-science imagery could also be utilized to qualitatively examine rapid storm-impact assessments (Figure 15) or to highlight unique morphological feature development, like beach scarps.

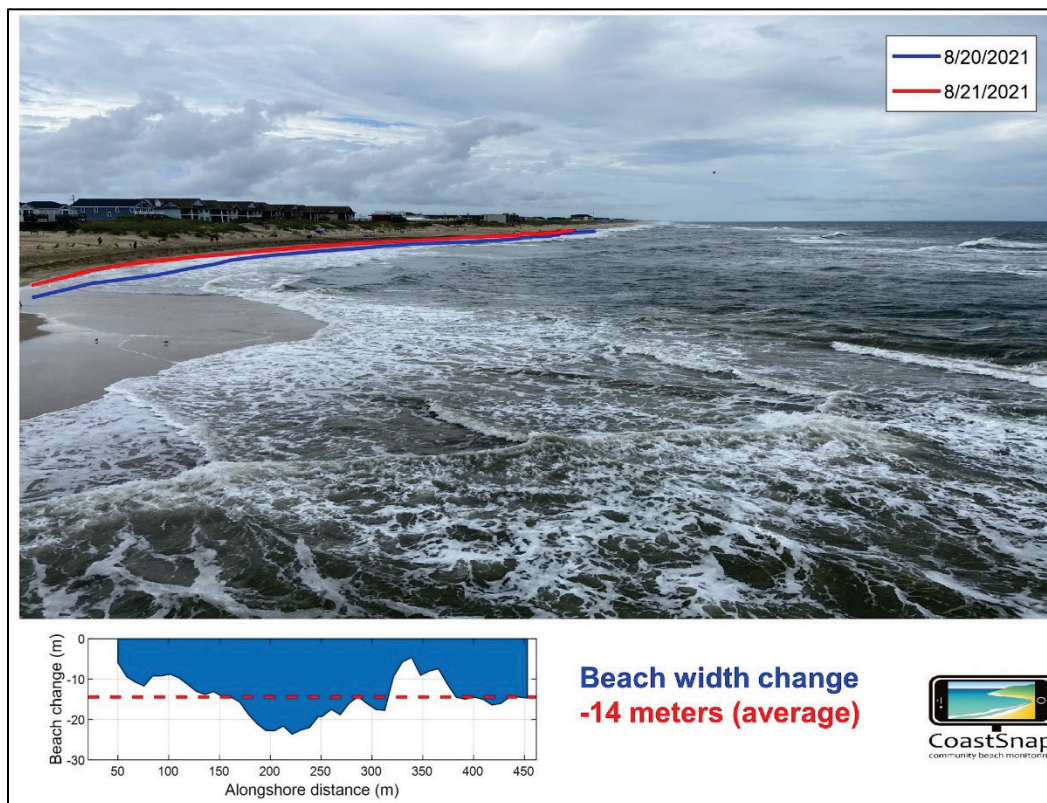
5.2 Community Outreach

There are ample opportunities for CoastSnap community outreach, both online and in person. CoastSnap hosts can use discretion to craft social media posts that communicate findings as time allows or when particular events of interest occur (e.g., Figure 14). With the high frequency of image submissions after implementing the QR code, this could occur on a weekly or even daily basis if needed. Online platforms provide an opportunity to synthesize takeaways from imagery data and clearly communicate with the public, in addition to answering questions posed online. The researchers have aimed to make posts visually compelling and understandable while also occasionally incorporating technical aspects and methodology.

The research team also presented the CoastSnap project to summer camps at Jennette's Pier. The team described the history and technological pieces of CoastSnap, showed data examples of long- and short-term shoreline evolution, storm impacts, and recovery. In addition, the team discussed how this tool may be useful to coastal managers and USACE districts dealing with erosion issues. The team has also connected with Science, Technology, Engineering, and Mathematics (commonly referred to as

STEM) advanced-placement high school teachers with the intention of growing partnerships for potential new stations or internships, or both. As CoastSnap expands, partnerships will be integral to help maintain stations, data streams, analysis, and public communication.

Figure 15. Storm impacts captured by CoastSnap shorelines before (*blue*) and after (*red*) the offshore passing of Hurricane Henri. *Bottom panel* shows beach-width change in the alongshore (numbers increase with distance from camera station).



5.3 Current Limitations

Image processing requires significant user input, despite overcoming challenges with image submission. As the regional CoastSnap network grows and photo submissions increase, the need for an automated file-management system and automated image-processing procedures will become a necessity. Currently, a user is required to manually download and name individual CoastSnap images one at a time. Each of the files must then be moved to a specific folder that the CoastSnap code, which is written in MATLAB, accesses. Future work may focus on incorporating Python for more efficient processing. The code makes use of an Excel database, which also requires significant user input to populate. Once the information in the database has been entered, the images are rectified

manually using preselected GCPs in the camera FOV using the MATLAB-based CoastSnap GUI. Once the image has been rectified, the shoreline is mapped and saved.

While the CoastSnap GUI has many strengths, it also suffers from some limited functionality. Despite having multiple images from a single day available, users are not able to specify which images to pick for shoreline-change analysis and plotting, often resulting in plots that are skewed due to images selected from different tidal stages. Instead, it would be ideal for users to select preferred images from a table of contents. Furthermore, shorelines can only be plotted in oblique space and not map space.

Currently, CoastSnap does not allow for input of measured water levels and run-up estimates for a specific image. Implementing run-up would require a custom script to either update the tidal file automatically with measured values or alter the GUI for input. The previous section highlights the error introduced by incorrect elevations which in the Jennette's case could range up to 18 m during large wave events.

5.4 Best Practices

5.4.1 Installation

There are many factors to consider when determining the location of a potential CoastSnap station. Low-angle oblique imagery presents rectification challenges, and elevation is paramount as it provides more FOV and improves image rectification. Next, a location that contains plentiful fixed structures for GCPs within the field of view is also critical; at least four well-distributed GCPs are required, but more than four are recommended so multiple rectification solutions can be explored. If available, a lidar system enables the rapid collection of an abundance of GCPs in areas not accessible by foot with an RTK-GPS.

5.4.2 Processing

The accuracy of CoastSnap-derived shorelines also hinges on the availability of robust environmental data (i.e., tides and waves; Figure 11).

Implementing measured water level is encouraged for best results.

However, if there are enough user submissions throughout the day and only general shoreline trends are desired, specific water levels are not necessary.

Adding run-up estimates improves accuracy for large-wave events but is not

needed for smaller-wave days. Note that incorporating run-up requires additional advanced coding beyond standard CoastSnap practice.

5.5 Recommendations

Ongoing ERDC research is focused on improving submission and processing routines. Utilizing the Esri Survey123 platform and QR code process, goals include automating the transfer of images from the online cloud to a local machine or server. Automated image processing in Matlab or Python will be run; then, the processed image with corresponding shoreline will be returned to the ESRI platform. Ideally, processed images will be viewable to outside users, and time intervals can be specified to examine shoreline change. A website or data viewer is in development to make results digestible to the public and serve as an outreach platform. Machine learning and automated feature-matching algorithms are also being investigated for feature matching to speed up processing and remove the need for manual processing on individual images. Since there are generally fixed structures in the field of view, feature matching should theoretically be achievable.

After conducting the pilot study, the researchers have developed a three-tier structure to assist districts in determining what CoastSnap setup is most suitable for their needs:

5.5.1 Tier 1—Outreach-Focused CoastSnap Station

The following points describe the most basic and lowest-cost approach for a CoastSnap station:

- installation of CoastSnap mount and signage for project information and submission process
- no MATLAB processing; align photos in Photoshop and qualitatively identify beach changes; share photos and educational posts with public
- pros: qualitative information on shoreline dynamics, storm impacts, and seasonal changes
- cons: lack of shoreline extraction and quantitative information

5.5.2 Tier 2—Standard CoastSnap Station

The following points describe the middle tier, which produces quantitative data:

- installation of CoastSnap mount and signage for project information and submission process
- collection of NOAA tide data (predicted) and generalized wave data (average wave height and period) for run-up estimate
- set up of Excel database and MATLAB processing workflow
- determination of optimal image rectification and rectify images within GUI
- pros: shoreline extraction provides quantitative information, good for detecting seasonal trends
- cons: potential for inaccurate shoreline extraction (refer to Figure 11), especially during high-wave events, limited functionality in GUI (e.g., image selection), shoreline change plotting options are limited

5.5.3 Tier 3—Scientific CoastSnap Station

The following points describe the top, most-involved quantitative CoastSnap tier:

- installation of CoastSnap mount and signage for project information and submission process
- collection of NOAA tide data (measured) and actual wave data to incorporate run-up using custom scripts outside of GUI
- set up of Excel database and MATLAB processing workflow
- determination of optimal image rectification and rectify images within GUI
- pros: more accurate instantaneous shoreline estimates that are ideal for directly calculating during and after storm shoreline impacts; custom scripts can allow for more plotting options, analysis and specified time intervals (e.g., Figure 9, Figure 10, Figure 12, Figure 13)
- cons: requires advanced Matlab programming knowledge

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Abbreviations

CIRN	Coastal Imaging Research Network
CLARIS	Coastal Lidar and Radar Imaging System
ERDC	US Army Engineer Research and Development Center
FOV	Field of view
FRF	Field Research Facility
GCP	Ground control point
GPS	Global Positioning System
GUI	Graphical user interface
NOAA	National Oceanic and Atmospheric Administration
QR	Quick-response
RMSD	Root mean square deviation
RMSE	Root mean square error
RTK	Real-time kinematic
SME	Subject matter expert
UNSW	University of New South Wales
USACE	US Army Corps of Engineers

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14. ABSTRACT This US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, technical report details the pilot deployment, accuracy evaluation, and best practices of the citizen-science, coastal-image monitoring program CoastSnap. Despite the need for regular observational data, many coastlines are monitored infrequently due to cost and personnel, and this cell phone-image-based approach represents a new potential data source to districts in addition to providing an outreach opportunity for the public. Requiring minimal hardware and signage, the system is simple to install but requires user-image processing. Analysis shows the CoastSnap-derived shorelines compare well to real-time kinematic and lidar-derived shorelines during low-to-moderate wave conditions (root mean square errors [RMSEs] <10 m). During high-wave conditions, errors are higher (RMSE up to 18 m) but are improved when incorporating wave run-up. Beyond shoreline quantification, images provide other qualitative information such as storm-impact characteristics and timing of the formation of beach scarps. Ultimately, the citizen-science tool is a viable low-cost option to districts for monitoring shorelines and tracking the evolution of coastal projects such as beach nourishments.					
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