# Appendix A:
# Identifying Priority Fixed-Site Monitoring Locations

## Background

In 2020, NOAA managers convened a group of subject matter experts (SMEs) for recommendations on cost-effective monitoring approaches to collect data to inform evaluation questions and determine LBSP management success (Vandiver et al. 2021). LBSP management outcomes and goals were identified across multiple spatial scales: BMP/Site, Watershed, and Nearshore Ecosystem. Corresponding evaluation questions were used to select indicators that are most sensitive to LBSP threats and, therefore, are most likely to provide meaningful data (over time and space) to address the questions. In addition, methodological considerations were discussed for each indicator. Using a Multiple Lines of Evidence (MLE) approach, it is anticipated that priority indicators could be monitored to collectively evaluate ecosystem response to LBSP management actions on Culebra (Lenwood and Giddings 2000).

Determining the results of watershed and site-level BMPs implementation on receiving nearshore habitats is complex, crossing multiple ecological boundaries, and once in the marine environment the signal from watershed restoration activities may be difficult to detect. However, monitoring priority indicators in the nearshore environment will be key to determining whether the scale of restoration is adequate to elicit nearshore environmental responses. To provide the greatest potential to detect change in the nearshore environment, as a result of LBSP management, over time, fixed monitoring locations should be identified. These fixed-sites should be located where the inputs from the watershed are most persistent so that any change in the nearshore resources can be attributed to runoff regimes that have been altered by restoration efforts on land. This requires an understanding of watershed hydrology and coastal hydrodynamics as well as the level of existing level LBSP exposure and anticipated changes to LBSP exposure due to management actions.

## Investigations to inform selection of nearshore fixed-sites

NOAA funded a series of coordinated investigations to: identify existing sediment and nutrients discharge points, identify predominant pollutant distribution patterns across nearshore habitats (i.e., seagrass and coral reef), and identify predominant *Sargassum* nearshore collection points. This information, combined with existing knowledge of LBSP management, will result in reasonable recommendations for siting of nearshore fixed stations. An overview of these studies and associated nearshore fixed-site selection process and outcomes is provided within.

### *Identify existing sediment and nutrients discharge points*

Nearshore fixed-sites should be located where the inputs from the watershed are most persistent so that any change in the nearshore resources can be attributed to runoff regimes that have been altered by restoration efforts on land. As such, NOAA contracted Protectores de Cuencas (PDC) to identify predominant watershed discharge points. Through local knowledge and in-field investigations PDC produced a GIS shapefile that identified 25 discharge points to the nearshore (Figure 1).

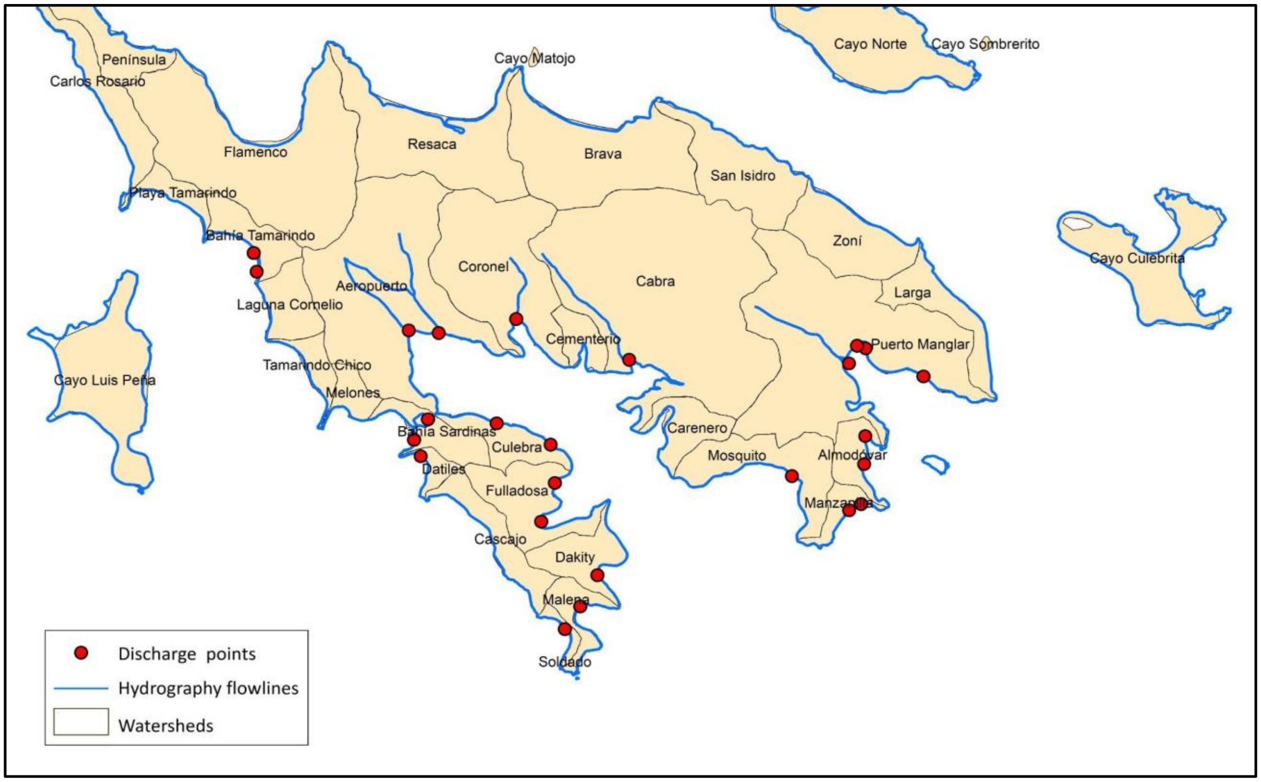



Figure 1. Watersheds and main discharge points on Culebra.

## *Predominant pollutant distribution patterns across nearshore habitats*

Selection of nearshore fixed-sites requires an understanding of predominant pollutant distribution patterns to ensure site selection is representative of target pollutants. A series of investigations were utilized to determine coastal hydrodynamics and pollutant distribution patterns in and around Culebra's nearshore coastal habitats. These included: spatially refined hydrodynamic modeling, identification of sediment plumes and / or resuspension, and synoptic surveys to confirm distribution of pollutants.

### Spatially refined hydrodynamic modeling

Working under the assumption that material will move with prevailing currents, a greater understanding of the long-term oceanographic transport pathways as well as insight into the impacts of short-term event driven processes may inform where terrigenous sediment deposition occurs in the nearshore and how it may move through the system. NOAA contracted Miguel Canals, via a subcontract to PDC, to analyze existing, freely available numerical model output from high-resolution wave and circulation models to develop maps of hydrodynamic variables associated with Culebra's wave climate and circulation regime. In particular, the wave climate analysis utilized data from a high-resolution wave model that has been developed to simulate Puerto Rico's wave climate at a 3-hour time step from January 1, 1979 to December 31, 2018. This simulation provided 40 years of wave model output that is freely available through the Puerto Rico / USVI High-Resolution Wave Climate Atlas interface. The coastal circulation analysis utilized freely available model output from CARICOOS Finite Volume Coastal Ocean Model (FVCOM) that has been running in experimental but operational mode since February 2018.

The study resulted in a series of maps, KMZ files, and GIF animations that provided insight into predominant wave energy and currents. On average, wave height and power density (kW/m) were greatest along the northernmost coastline of Culebra (Figures 2 and 3). However, the majority of the outermost coastlines of Culebra saw significant increases in wave height and power density under maximum conditions (Figures 4 and 5). Similar to wave trends, the strength of currents is typically greatest along the periphery of Culebra's coastlines with current strength being lesser inside the bays. In general, prevailing current directions approach Culebra from the Southeast moving northward, near the mouth of Ensenada Honda (Figure 6). The current bifurcates the island at this point with prevailing flows moving northerly along the periphery of the island on the east and west sides. However, direction of currents inside Ensenada Honda and Bahia Puerto Manglar vary throughout daily tidal cycles and likely are influenced by wind and wave energy (Animation 1 and 2).

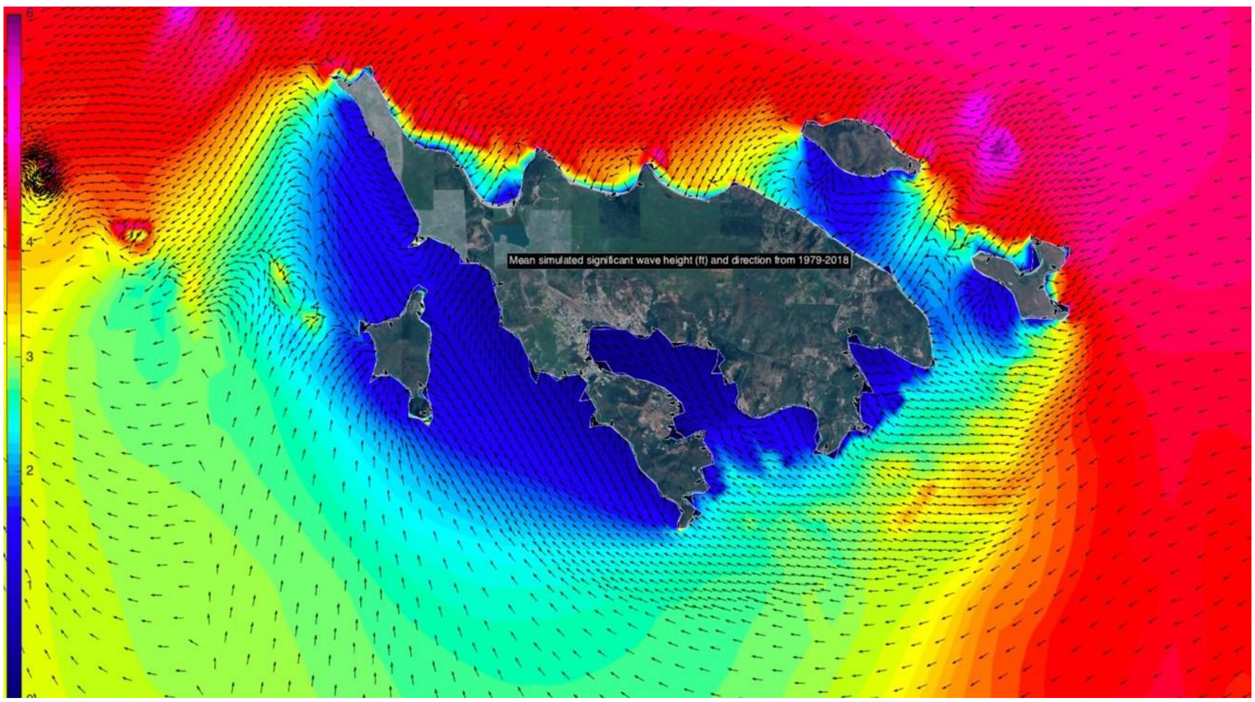



Figure 2. Mean significant wave height (ft) around Culebra based on a 3-hour time step model from 01/0/1979–12/31/2018. Data SIO, NOAA, U.S. Navy, NGA, GEBCO; image© 2021 CNES/Airbus; Image© Maxar Technologies.

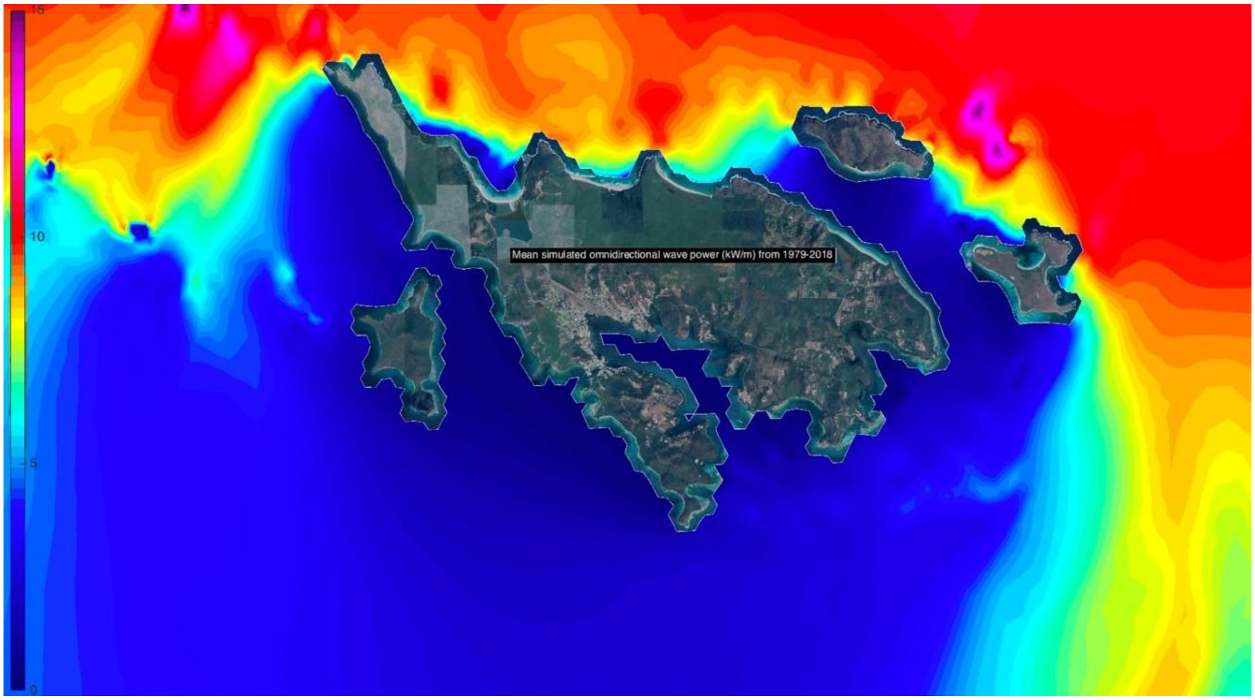



Figure 3. Mean wave power density (kW/m) around Culebra based on a 3-hour time step model from 01/0/1979–12/31/2018. Data SIO, NOAA, U.S. Navy, NGA, GEBCO; image© 2021 CNES/Airbus; Image© Maxar Technologies.

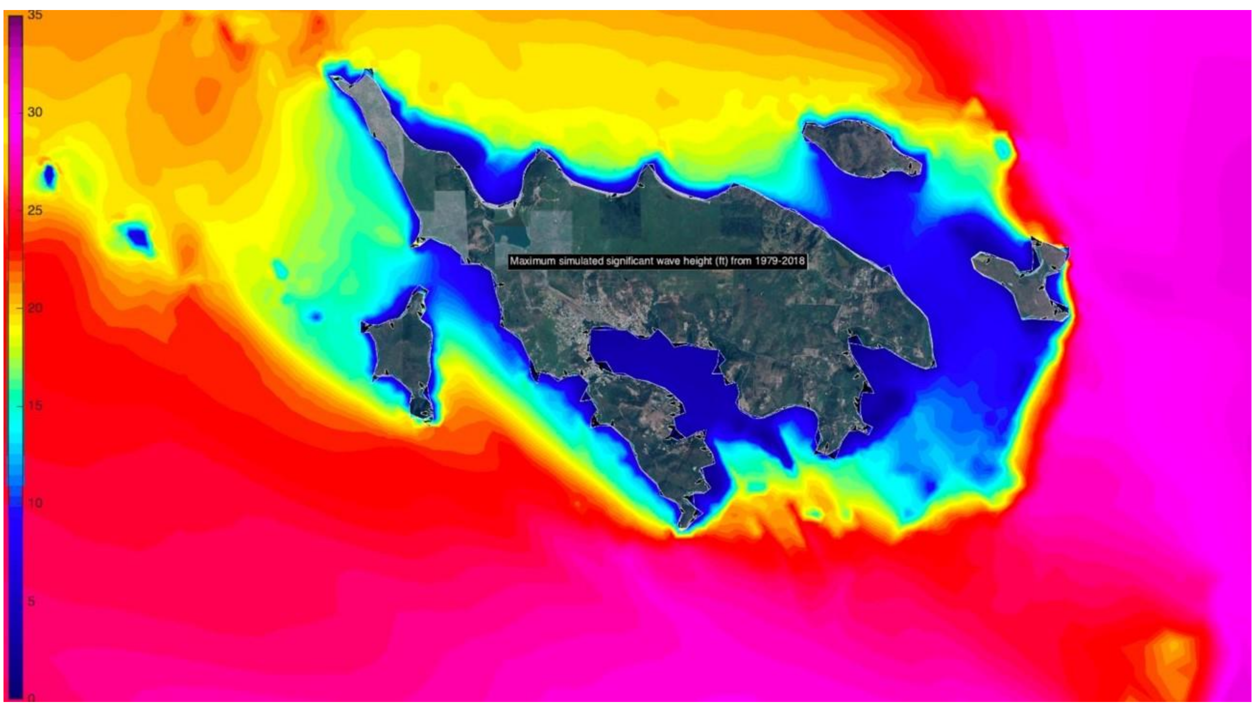



Figure 4. Maximum simulated significant wave height (ft) around Culebra based on a 3-hour time step model from 01/0/1979–12/31/2018. Data SIO, NOAA, U.S. Navy, NGA, GEBCO; image© 2021 CNES/Airbus; Image© Maxar Technologies.

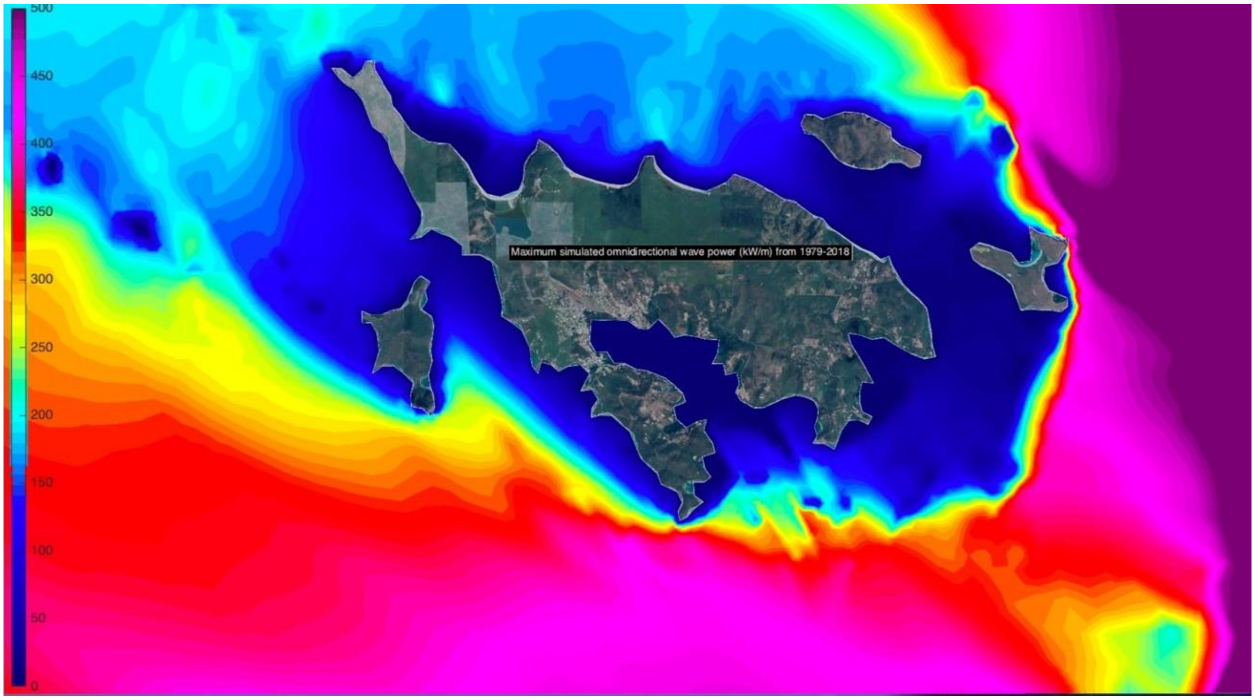



Figure 5. Maximum simulated wave power density (kW/m) around Culebra based on a 3-hour time step model from 01/0/1979–12/31/2018. Data SIO, NOAA, U.S. Navy, NGA, GEBCO; image© 2021 CNES/Airbus; Image© Maxar Technologies.

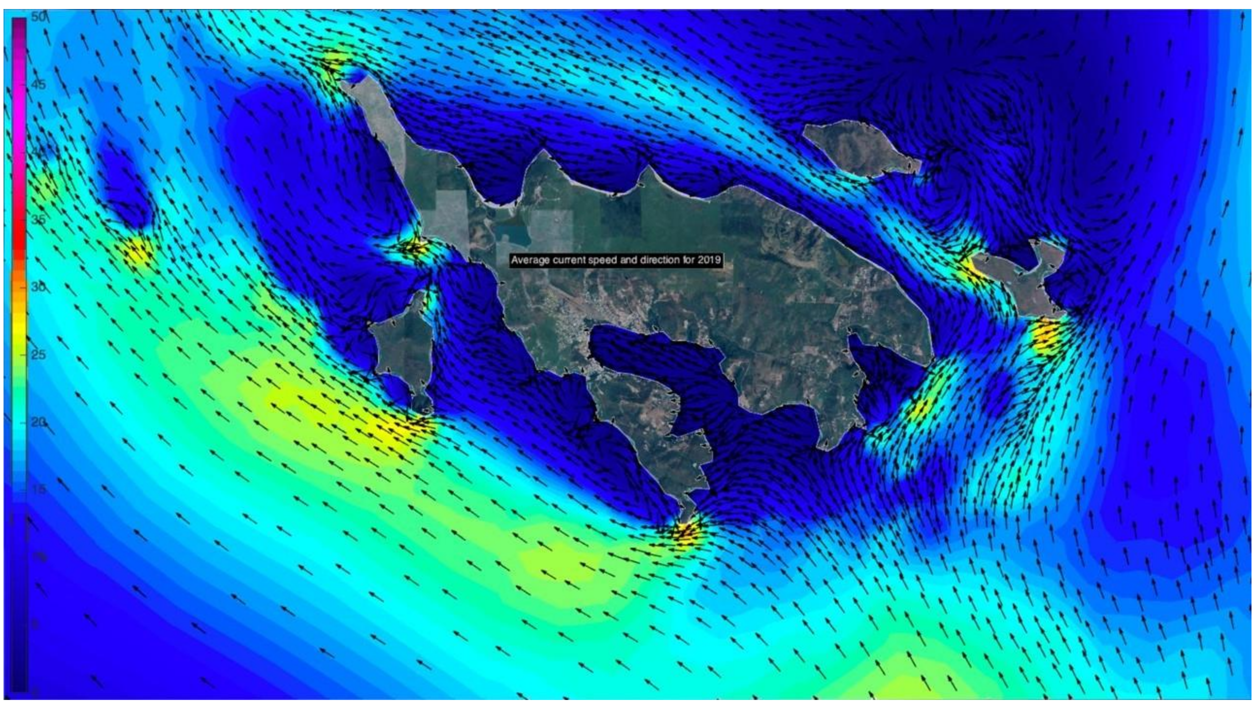
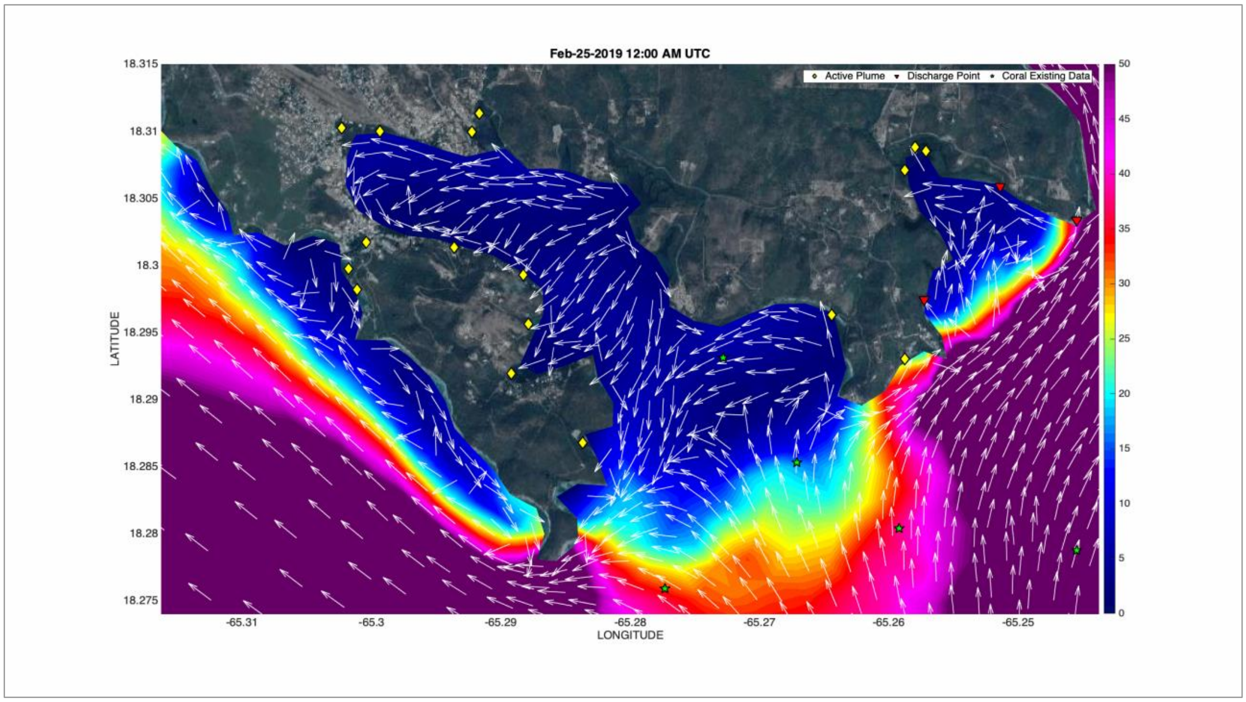
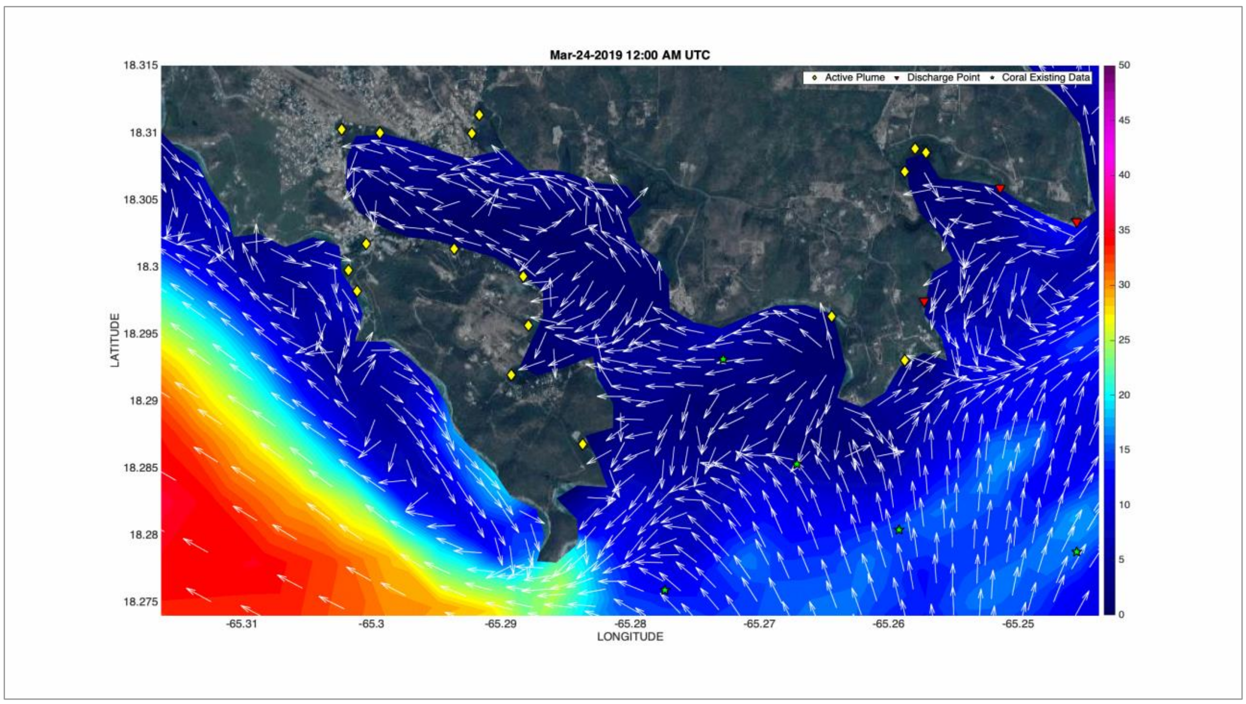



Figure 6. Maximum wave power density (kW/m) around Culebra based on a 3-hour time step model from 01/0/1979–12/31/2018. Data SIO, NOAA, U.S. Navy, NGA, GEBCO; image© 2021 CNES/Airbus; Image© Maxar Technologies.




Animation 1. Water circulation patterns in Ensenada Honda and Bahia Puerto Manglar February 25–26, 2019.




Animation 2. Water circulation patterns in Ensenada Honda and Bahia Puerto Manglar March 24–25, 2019.

## Identify sediment plumes and/or resuspension

Review of existing imagery can provide insight into existing plumes and / or resuspension which can provide valuable insight into pollutants distribution patterns in and around Culebra's nearshore coastal habitats. NOAA contracted William Hernandez, via a contract to Horsley Witten Group (HWG), to analyze high spatial resolution imagery (10 m) to identify plumes and surface sediment present in imagery. A total of 78 Sentinel 2 Multi Spectral Imager (MSI) images were identified and downloaded free of charge from the Copernicus Open Access for Sentinel 2 Data (https://www.sentinel-hub.com/explore/copernicus-data-space-ecosystem/) for Culebra from 2016–2021. The products were collected and processed at Level 2 (surface reflectance) with atmospheric correction applied. Datasets were developed in true color and enhanced color (bands combined 321) to improve detection of benthic features and turbidity and plumes in the water column. Some images were collected even with clouds present if these did not cover the whole island or plumes / turbidity were visible. Images with sunlight were discarded unless plumes were visible in the clear areas.

Suspended sediments were found in varied locations throughout the 78 images; however, the frequency of events was greater in certain locations. In particular, suspended sediments occurred in Ensenada Honda the most of all locations, with suspended sediments observed in 50 of the 78 images. This site was followed by Bahia Puerto Manglar which observed suspended sediments in 10 images. No major plumes were observed for Datiles and Fulladosa, except after hurricane Maria (Figure 7). Suspended sediments were observed in 15 images in the north of Culebra including Flamenco, Resaca, Brava mainly due to high energy resuspension events. The high cloud cover and small bays and inlets combined with the spatial resolution limited the amount of LBSP features that could be observed. In addition, areas with darker non-reflective benthic cover like seagrass, limited the ability to distinguish sediments in the water column over these areas.

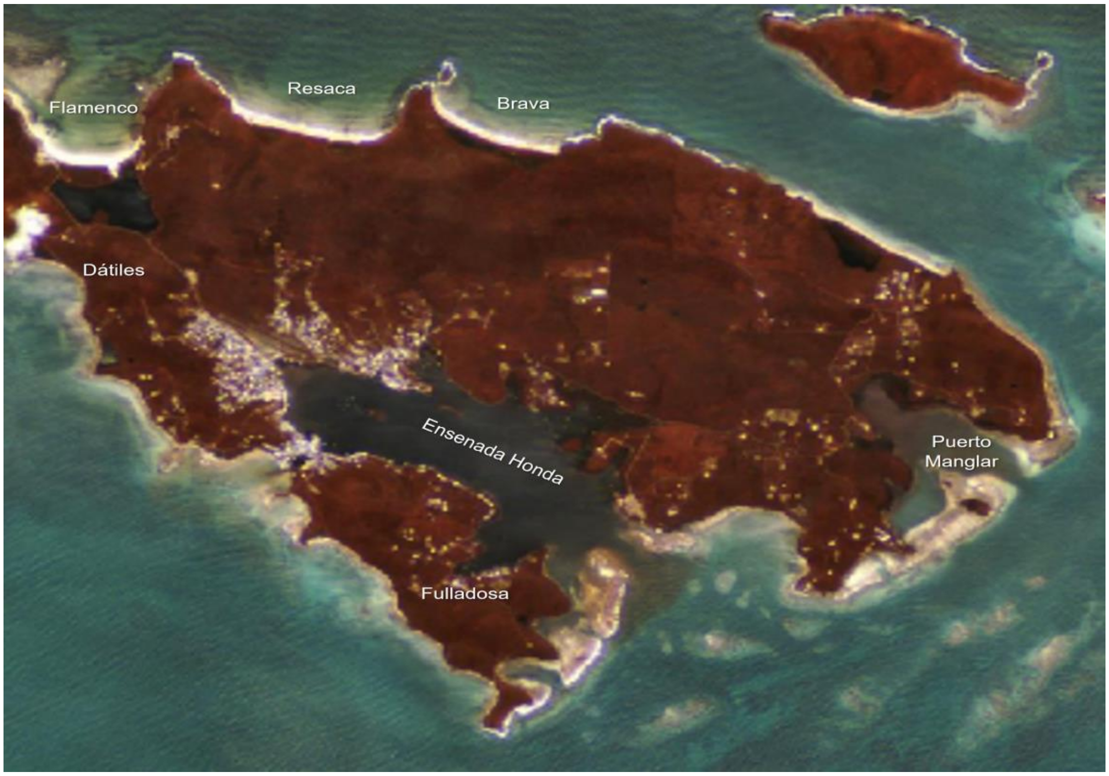



Figure 7. Enhanced composite satellite image showing plumes and turbid waters in Ensenada Honda, Fulladosa, Datiles and Puerto Manglar.

## *Site Classification*

The information provided from the highlighted investigations was combined with existing watershed and coastal habitat knowledge to develop a classification system for guiding the selection of nearshore fixed stations. Watersheds and adjacent receiving nearshore coastal waters were classified according to a range of characteristics listed in Table 1l the finalized watershed classification is presented in Table 2.

Table 1. Watershed and nearshore, coastal characteristics and classification. Associated maps are provided in the corresponding figures.

| **Characteristic** | **Classification** | **Methods** |
|---|---|---|
| Watershed Size<br>Figure 8 | Small,<br>Medium, Large | Watershed size was quantified and categorized where small = 0 to 147 acres, medium = 147 to 415 acres, and large = 414 to 1033 acres. These categories were defined by an ArcGIS histogram classification. |
| Watershed<br>Slope<br>Figure 9 | Low,<br>Moderate,<br>High | Mean and Maximum slope was estimated using the spatial analyst tool in ArcGIS. The outputs from this and the topography were analyzed to estimate low, moderate, and high slope categories. |

| Characteristic | Classification | Methods |
| --- | --- | --- |
| Hydrologic connectivity Figure 10 | Low, Moderate, High | High was identified by those sites that had 'streams' identified from the National Hydrologic Dataset. All other sites were deemed moderate since slopes are steep and it is well known that stormwater does drain from watersheds into the nearshore waters. |
| Watershed Pollutant Sources | Low, Moderate, High | Using subject matter expert input to estimate LBSP threats relative to other sites. |
| Nearshore Pollutant Distribution | Retains, Flushes | Determined through analysis of CariCOOS models of mean current and waves values and direction and satellite imagery of sediment resuspension / plumes. Retains, was defined as those locations that were found within embayments that had consistent current and wave directions that appeared to trap pollutants in the embayments. This was also validated by satellite imagery. Flushes were those places where consistent current or wave energy ran parallel to the land and did not appear to distribute pollutants via satellite imagery. |
| Restoration Figure 11 | Low, Moderate, High | A footprint of 'restored area' was estimated by creating a 3-meter buffer around the stabilized unpaved roads layer. The resulting polygons were separated by watershed and quantified as a proportion of watershed area. These values were then categorized by low, moderate, high - with the acknowledgment that the Floating Treatment Wetland at the Culebra WWTP in the Cabra watershed was in addition to the unpaved roads. |
| Residence time | Low, Moderate, High | Residence time was categorized by evaluating the CariCOOS models of mean wave and currents and the sediment plumes / resuspension in imagery. High value was applied to those sites in the interior of Ensenada Honda where consistent sedimentation was found in the imagery. Moderate was applied to those sites that found frequent sedimentation in the imagery or where currents/ winds suggested that pollutants were likely 'trapped' in water bodies frequently. Low was applied to all other sites. |
| Current / wave strength | Low, Moderate, High | Determined through analysis of CariCOOS models of mean current and waves values and direction. Low values are those typically inside embayments that denote low values and multi directions suggesting. Moderate values are those that either show higher values of currents or waves and have a consistent direction of flow. |

| Characteristic | Classification | Methods |
|---|---|---|
| | | High values are those that have either high currents or wave energy. These sites are not preferred for monitoring since oceanic currents / waves would likely mute any signal from the watershed. |
| *Sargassum* collection Figure 12 | Low, Moderate, High | Determined through analyzing mapping outcomes from the Nearshore WSG |

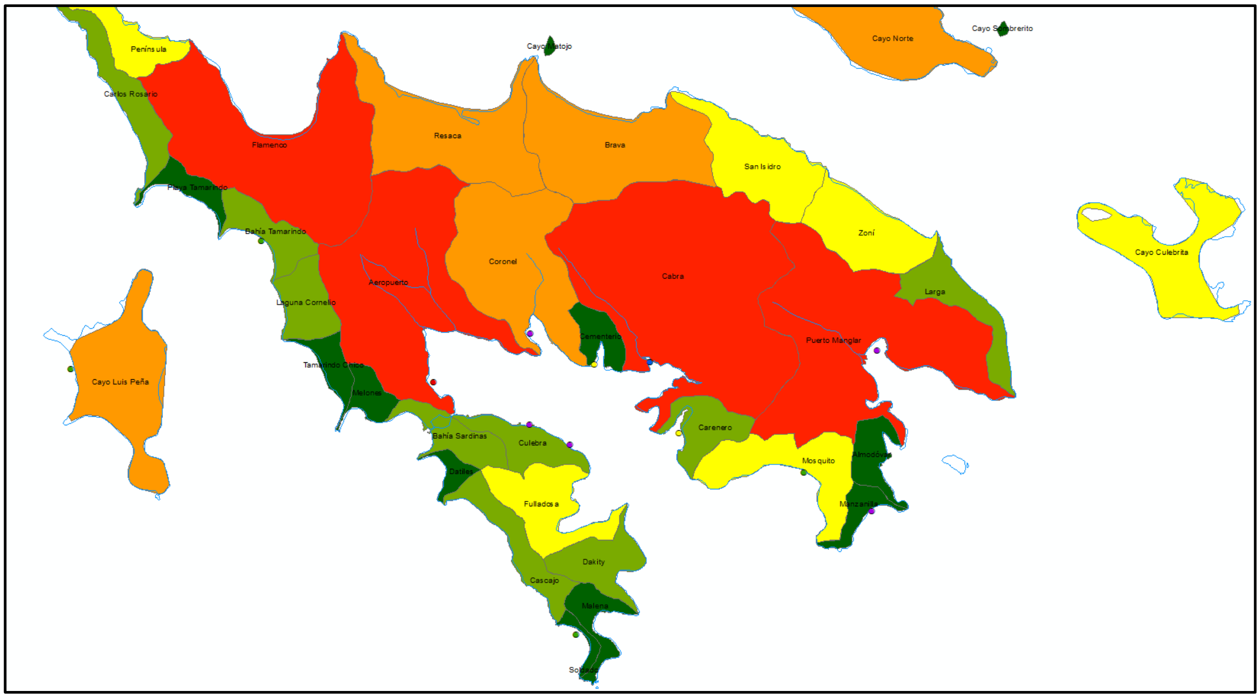



Figure 8. Classification of watershed size where low (light/dark green) = 0 to 147 acres, moderate (yellow/orange) = 147 to 415 acres, and high (red) = 414 to 1033 acres.

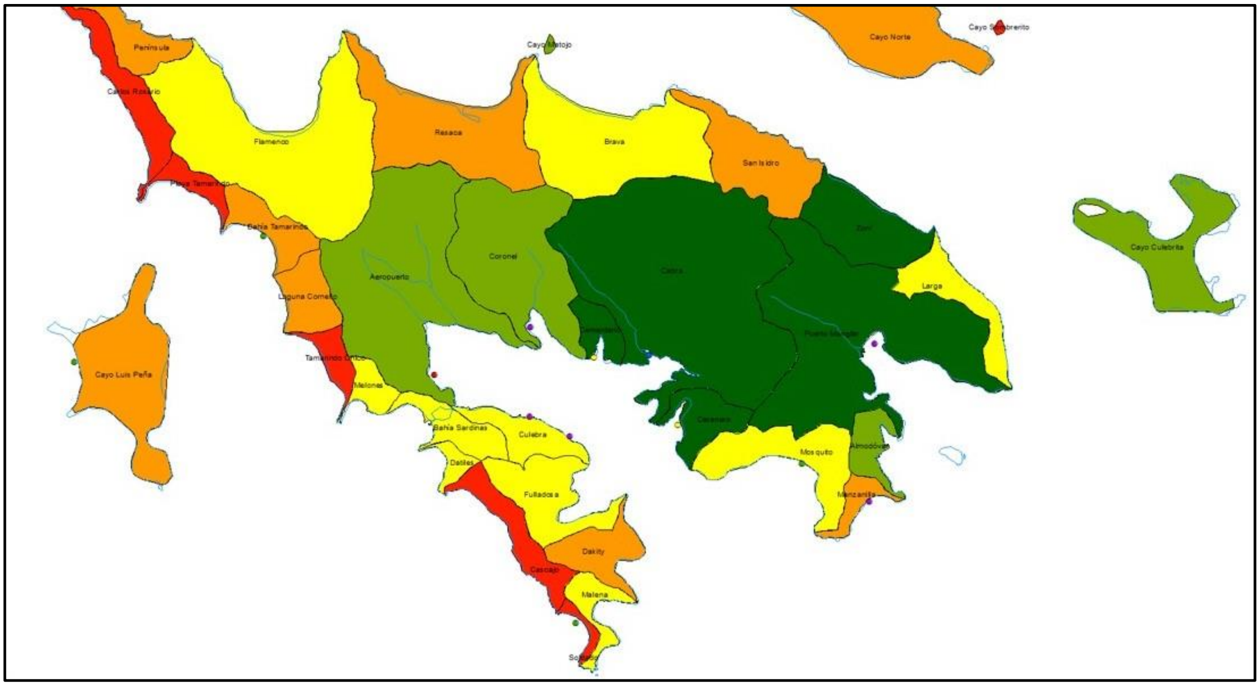


Figure 9. Classification of watershed mean slope; low (light/dark green), moderate (yellow/orange), and high (red).

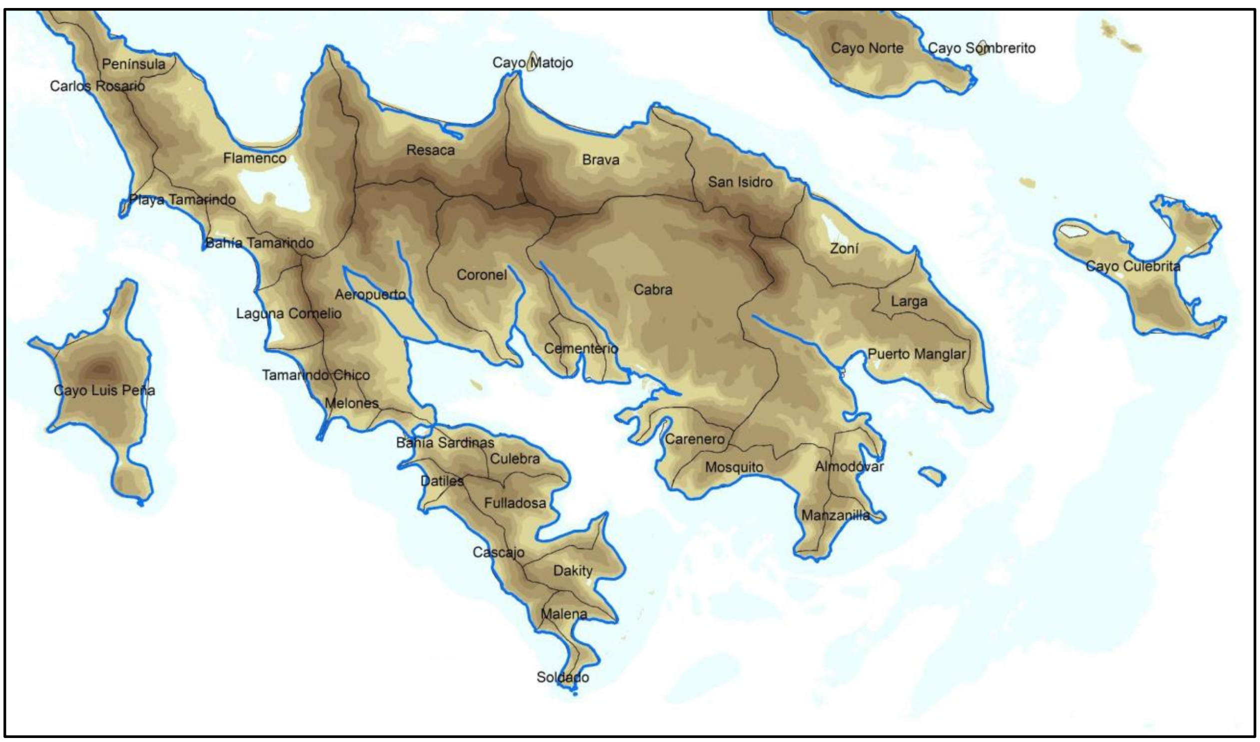



Figure 10. Hydrologic connectivity

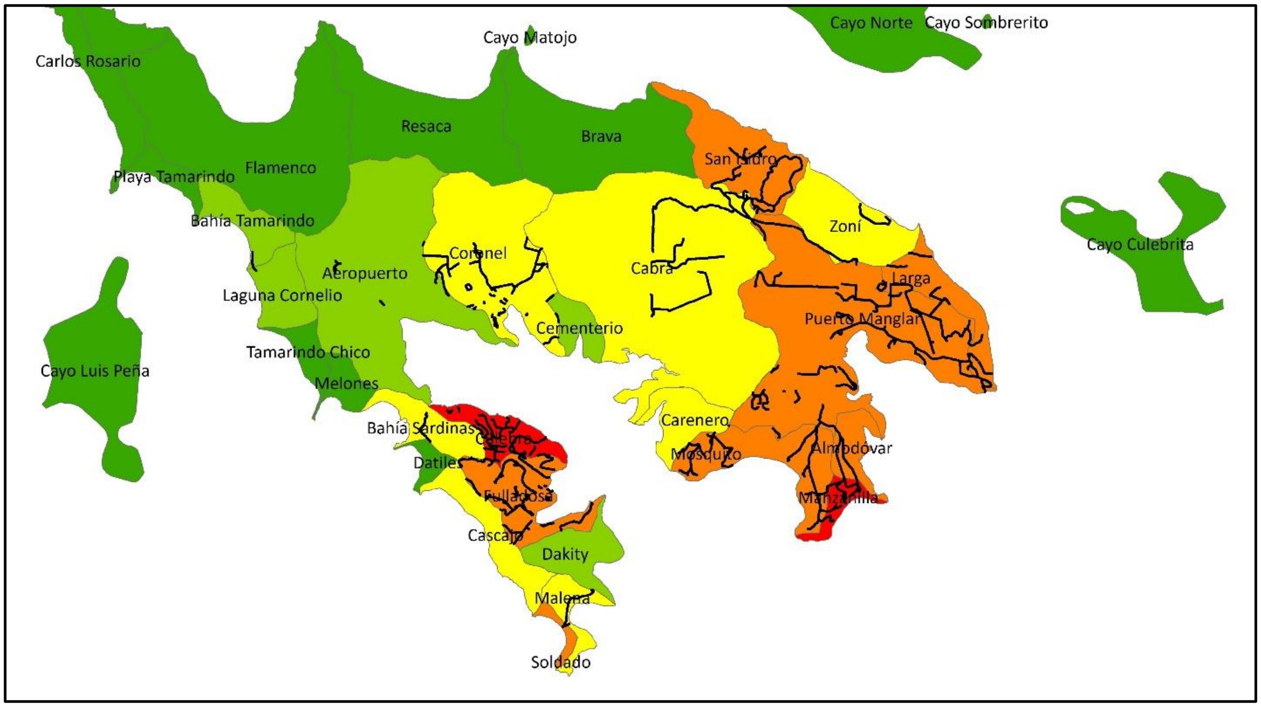



Figure 11. Restoration proportion; none (dark green), low (light green/yellow), moderate (orange), and high (red). Stabilized unpaved roads are outlined in black.


Figure 12. *Sargassum* accumulation areas in Culebra’s embayments identified by subject matter experts during the nearshore working group.

Table 2. Summary of watershed classification based on characteristics listed in Table 1. Red = negative reference, green = positive reference, yellow = LBSP control, blue = LBSP restoration.

| Watershed | Size | Slope | Connectivity | Pollutant sources | Pollutant distribution | Restoration | Residence time | Current / wind strength | *Sargassum* collection |
|---|---|---|---|---|---|---|---|---|---|
| Aeropuerto | Large | Low | High | High | Retains | Low | High | Low | Moderate |
| Little Cabra | Small | Low | Moderate | Low | Retains | Low | Moderate | Low | Low |
| Cementerio | Small | Low | Moderate | Low | Retains | N/A | High | Low | Moderate |
| Casa Azul (Culebra) | Small | Moderate | Moderate | Moderate | Retains | High | High | Low | Low |
| Fulladosa | Medium | Moderate | Moderate | Moderate | Retains | High | High | Low | Moderate |
| Bahia Tamarindo | Small | Moderate | Moderate | Moderate | Flushes | Low | Low | Moderate | Low |
| Mosquito | Medium | Moderate | Moderate | Low | Flushes | Moderate | Low | Moderate | Low |
| Coronel | Medium | Low | High | High | Retains | Moderate | High | Low | Low |
| Culebra | Small | Moderate | Moderate | Moderate | Retains | High | High | Low | Low |
| Manzanillo | Small | Moderate | Moderate | Moderate | Flushes? | High | Moderate | Moderate / High | Moderate |
| Puerto Manglar | Large | Low | High | Moderate | Retains | Moderate | Moderate | Moderate | High |
| Cabra | Large | Low | High | High | Retains | High | High | Low | Low |

## Site selection

Ideally, nearshore fixed-sites would be selected to support a Before After Control Impact (BACI) design; where 'LBSP Restoration' sites are downstream of watersheds with LBSP management and 'LBSP control' sites represent similar conditions as the restoration sites minus the management. In reality, some of the sites do not have before data and some do—no one watershed is exactly like another and coastal hydrodynamics vary across space. So, in addition to the control and impact sites there was an interest in including positive and negative reference sites that are representative of the lowest and highest LBSP threat, respectively. This would provide some ability to evaluate change relative to the control as well as, relative to positive and negative reference sites.

Site classifications were used to identify preferred characteristics of nearshore fixed-monitoring sites that represent the following: LBSP restoration, LBSP control, and positive and negative references. Preferred nearshore fixed monitoring station (<6m) were identified based on the following criteria:

1. Coastal hydrodynamic impacts (categorized as current and wind energy) should be low to moderate to ensure that signals from the watershed have a better chance of being seen in the monitoring data.
2. Pollutant source classifications should be assigned to monitoring sites such that negative reference = high, positive reference = low, and LBSP restoration = moderate to high.
3. Restoration categories should be assigned to monitoring sites such that reference sites = low or n/a and LBSP restoration sites = moderate to high.
4. All remaining characteristics are likely to vary across sites. The fixed monitoring stations should have an equal representation of the range of characteristics among restoration and control sites

A final consideration was made, to include locations where baseline (pre-restoration watershed restoration activities) seagrass and water quality monitoring surveys had been completed in 2014. Accordingly, potential nearshore fixed-sites were narrowed down to 13 locations (Table 3). A series of synoptic surveys were used to evaluate in-field conditions, confirm locations for nearshore fixed-sites, and deploy permanent markers (Figure 13).

Table 3. Nearshore fixed monitoring station locations.

| **Monitoring Station** | **Code** | **Watershed** | **LBSP Treatment Group** | **Latitude** | **Longitude** |
|---|---|---|---|---|---|
| Aeropuerto | AP | Aeropuerto | Negative Reference | 18.3083690 | -65.2979940 |
| Cabra | CA | Cabra | LBSP Restoration | 18.3059370 | -65.2813820 |
| Casa Azul | CAZ | Culebra | LBSP Control | 18.3006040 | -65.2899960 |
| Cementerio | CM | Cementerio | LBSP Control | 18.3070770 | -65.2854440 |
| Coronel | CO | Coronel | LBSP Restoration | 18.3088810 | -65.2902890 |
| Fulladosa Bay | FDB | Fulladosa | LBSP Restoration | 18.2957150 | -65.2873460 |
| Fulladosa Point | FDP | Fulladosa | LBSP Control | 18.2968560 | -65.2858520 |
| Fulladosa Ramp | FDR | Culebra | LBSP Restoration | 18.2995720 | -65.2882960 |
| Little Cabra | LC | Cabra | LBSP Control | 18.3020900 | -65.2804920 |
| Mosquito | MQ | Mosquito | Positive Reference | 18.2920310 | -65.2639030 |
| Puerto Manglar Control | PMC | Puerto Manglar | LBSP Control | 18.3057740 | -65.2566650 |
| Puerto Manglar Reference | PMD | Puerto Manglar | Positive Reference | 18.3050480 | -65.2510630 |
| Puerto Manglar Treatment | PMT | Puerto Manglar | LBSP Restoration | 18.3057570 | -65.2517240 |

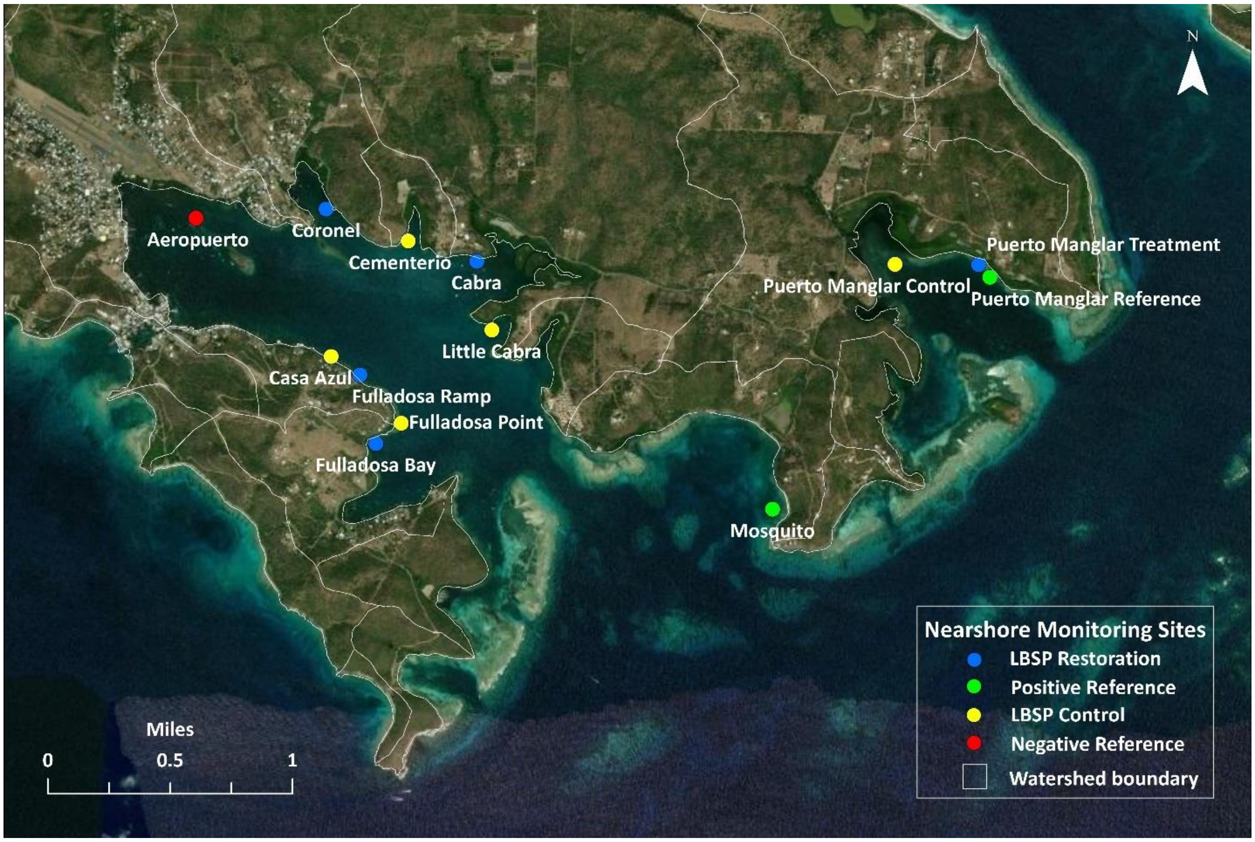



Figure 13. Nearshore fixed monitoring sites.