A Broad Scale Assessment of Seagrass Physical Disturbance after Hurricanes Irma and Maria

Assessment Report submitted by NOAA to the FEMA Natural and Cultural Resources Recovery Support Function

Revised & Updated Version

Introduction

Purpose

This cursory-level rapid assessment was devised to provide a basic understanding of whether seagrasses incurred hurricane related physical disturbances in 2017, and how widely the disturbances were distributed throughout the seascape. During the 2017 storm season, Puerto Rico experienced severe impacts from two major hurricane systems, Hurricane Irma (September 2, 2017) and Hurricane Maria (September 20, 2017). Multiple entities initiated various efforts to document and assess the effects these storms had on the natural resources of Puerto Rico and adjacent islands. This assessment was initiated to complement other FEMA coastal and water quality assessments investigating direct and indirect injuries to seagrass and coral benthic habitats. The study assessed physical disturbances to the area's benthic communities, specifically seagrass, at a broad island-wide scale.

Background

Seagrass habitats create distinct underwater features visible in remotely sensed imagery. Researchers and natural resource managers routinely use imagery data to map and quantify seagrass distributions, and with repeated mapping events, can detect changes over time in seagrass areal cover (Sherwood et al. 2017, Hernandez-Cruz et al. 2006). Acute episodic perturbations or disturbances like hurricanes may have direct impacts on the physical structure of seagrass beds and communities. Hurricane and strong storm related winds generate waves and intense storm surge. These hurricane-induced waves in addition to currents can cause breakage of seagrass above ground biomass (leaves and shoots) and uprooting of below ground biomass (Michot et al. 2002). Hurricane wind, wave, and current energy can also generate sediment movement in various ways. Hurricane generated energy can cause scouring of the bottom sediments with enough force to completely uproot and remove seagrass plants. Sediment movement can displace material that redistributes within the ecosystem with various consequences. Sediments deposited onto benthic habitats such as seagrass can cause burial of the live plant material. In addition, inputs of sediments eroding from terrestrial sources such as shorelines and terrestrial sediments transported via riverine freshwater inflows will enter the marine environment and can alter sediment depths, bury plant material, and create poor water quality conditions (Tilmant et al. 1994).

Research shows, natural perturbations such as storms and sedimentation processes (erosion and burial by re-suspended and moving sediments) result in observable changes to the seascape as well as changes in patterns of seagrass distribution (Koch et al. 2006). This assessment will use readily observable disturbances of the land and seascapes, which have possible causal relationships to the 2017 hurricane events, to identify any associated changes in seagrass coverage. A suite of disturbance types identified for use as indicators guided the project's landscape-level change detection process. The disturbance indicators are elements characterized as visible, broadly distributed, landscape features, known locations, or observable environmental impacts that can be influential in rapidly reviewing and assessing imagery.

Indicators of Disturbance Types

1. **Major terrestrial discharge points.** Changes in sediment dynamics around the mouths of discharge points may indicate physical disturbance via scouring or seagrass burial. The impacts may have secondary indirect impacts on water quality. Characteristics to look for: turbidity plumes of milky white and light brown colored water associated with the discharge points or expansion of light colored non-vegetated sands.
2. **Eroding Shorelines.** Changes in shoreline vegetation and sediment extent, spatial arrangement, or orientation may indicate burial of adjacent resources. Characteristics to look for: expansion of light colored non-vegetated sands and differences in the placement of wrack lines during different time periods. Changes may also be observed in adjacent tidal flats or sand bars.
3. **Hurricane related vessel groundings.** May indicate physical disturbance with loss of above and or below ground biomass. Characteristics to look for: vessels on their side or damaged and propeller scars.
4. **High reflectance areas apparent in post-hurricane imagery.** Seagrass and submerged aquatic vegetation generally produce low reflectance because of their ability to absorb light. From a visual perspective, seagrass habitats generally appear darker than non-vegetated areas of the sea floor (Dekker et al. 2006). In contrast, high reflectance areas are light, bright, or white coloring in imagery.
5. **Previously identified vulnerable areas.** Locations identified in existing reports as having seagrass or other important benthic resources that are also vulnerable to poor water quality or anthropogenic stressors. Other areas of significance include those identified as protected in some capacity such as preserve or natural reserves.

Methods

A typical broad scale seagrass survey would require pre- and post-storm seagrass distribution data to determine changes in habitat extent due to the event. The assessment would include mapping the distribution and GIS change analysis as well as in-field data collection to qualify actual impacts. The resources available to conduct this type of assessment were limited. Due to time and data constraints, no in-field data collection or acquisition of project specific imagery were possible. As an alternative, a rapid review of pre- and post-hurricane imagery was conducted that concentrated on identifying and locating key indicators of broad-scale seagrass disturbance. Locations throughout Puerto Rico suspected to be affected by the selected disturbance agents were investigated in pre- and post-hurricane imagery. Detectable changes were determined by visually comparing pre-hurricane imagery and existing benthic habitat maps to post-hurricane imagery.

Assessment Locations

The broad-scale study focused on assessing areas impacted by Hurricanes Irma and Maria. The review included coastal benthic habitats, limited to those no more than approximately 5 km offshore, surrounding the main island of Puerto Rico as well as Vieques, and Culebra. Availability and quality of imagery restricted the offshore extent of the study and did not allow for review of areas of particular interest including Caja de Muerto, La Cordillera Reefs, and areas around the northwest portion of Vieques. The rapid imagery review process directed assessment efforts to known locations to target the presence of disturbance indicators (Table 1). Non-targeted review of the imagery meant rapidly scanning the full breadth of available images, not just specific pre-selected locations, searching for features representative of disturbance indicators. The non-targeted review scanned imagery at 1:24,000 and often 1:12,000 zoom scales to rapidly visualize disturbed features. There was no formal tracking of what portions of images were scanned for indicators unless a disturbance was digitized and captured in the data collection process.

Table 1. Targeted locations of disturbance indicators pre-selected for review

Indicators: *Pre-Selected Location Descriptions*
Major Discharge Points (Rivers):
Rio Camuy
Rio Grande de Arecibo
Rio Grande de Manati
Rio de la Plata
Rio Hondo
Canal Rio Bayamon
Cano Aguas Frias
Rio Grande de Loiza
Rio Coamo
Rio Descalabrado
Rio Jacaguas
Rio Bucana
Rio Portugues
Rio Matilde
Rio Macana
Rio Guayanilla
Rio Yauco
Rio Loco
Rio Grande de Anasco
Vessel Groundings: *Various coordinates*

Continued Indicators: *Pre-Selected Location Descriptions*
Previously Identified Vulnerable Areas:
Caja de Muerto
La Cordillera Reefs
Culebra
Ensenada Fulladosa
Guanica, Ponce, Santa Isabel, San Jacinto
La Parguera Natural Reserve
GIS Layers of protected areas
Eroding Shorelines: *Various named beaches*

Source Data

Remotely sensed data such as satellite and aerial imagery are commonly used to visually interpret and determine the extent of features within the marine seascape (Bauer et al. 2012, Sherwood et al. 2017). Easily accessible imagery services from ESRI provide satellite imagery for the world with high-resolution aerial imagery added for many regions. The ESRI world imagery layer was used to access pre-hurricane imagery with various acquisition dates, resolutions, and sources. In general, by reviewing metadata available for discrete images within the mosaic, many of the images used for assessment comparisons were from the 2013 to 2016 period with a resolution of 1 m to 0.5 m or better. The Environmental Response Management Application (ERMA) service provided September 2017 post-hurricane data. NOAA's Ocean Service, National Geodetic Survey (NGS) published the data titled "Hurricane Maria: Emergency Response Imagery of the Surrounding Regions." The NOAA Remote Sensing Division acquired the imagery at altitudes of 2,500 to 5,000 feet. The resulting ground sampling distance for pixels was 15 cm. The imagery is a rapid response product for visual analysis of damaged areas and is not intended for mapping, charting, or navigation. Imagery resolution varied but were all of sufficient resolution for project purposes.

Additional spatial data sets assisted in the study's directed review of disturbance indicators at specific locations. All datasets with the exception of vessel groundings were compiled from publically available online databases and resources. Benthic habitat data was used for directing the disturbance identification review as well for analysis and interpretation of results. The best available habitat data included using a combination of NOAA's 2001 benthic habitat data for Puerto Rico, with updated replacement mapping for the southwest and northeast areas using 2010, 2012 and 2015 data, respectively. Under the Emergency Support Function #10 – Oil and Hazardous Materials Response, the Coast Guard and other agencies identified grounded vessels for environmental cleanup and disposal. The coordinates for hurricane-related vessel groundings were reviewed for apparent damages to seagrass resources. The spatial extent of many locations pre-selected for review as previously identified vulnerable areas (disturbance indicators) were included in the "U.S. Marine Protected Areas Boundaries: MPA Inventory (2017)" data layer. The MPA Inventory layer is an inventory of place-based marine conservation efforts under U.S. federal, state, territorial, local, and tribal jurisdiction. The "Caribbean

Landscape Conservation Cooperative 2016 Puerto Rico Protected Areas Database" is another GIS data set that provided additional spatial information for vulnerable areas. The Environmental Sensitivity Index for Puerto Rico, produced by NOAA and partners in 2000, served as a quick GIS-based reference and guide to locate human and environmental resources of interest for this study such as marinas, recreational beaches, rivers, and critical habitats of threatened and endangered species.

Data Collection and Analysis

Unlike a traditional habitat mapping process where the extent of an entire habitat feature is delineated, this process delineated only the noted differences in identifiable benthic features overtime. A review of the pre- and post-hurricane imagery was conducted by displaying the data side by side on dual monitors using the Geographical Information System (GIS) program ArcMap 10.5.1. A simple set of rules aided in decision-making during the change detection process. If the relative spectral signature and reflectance (i.e. brightness) of a feature significantly changed when compared in images of two different time-periods, disturbance to the sea floor bottom was assumed. Based the understanding that seagrass and other biological resources have dark spectral signatures (Bauer et al. 2012), a noted transition to lighter or brighter signatures in the post-hurricane data was indicative of disturbance of the resource or change to an un-vegetated state. If disturbance features such as turbidity plumes were present in the pre- and post- hurricane imagery it suggested an area might be routinely subjected to that disturbance type without the influence of hurricane conditions. Therefore, detection of a 2017 post-hurricane instance in an area regularly subjected to the disturbance type must indicate a larger extent or more intense display of the negative affect for documentation in the dataset. In addition, some changes to biological cover observed were too small to qualify as landscape-level changes and would be too time consuming to delineate. In those instances, every attempt was made to review the surrounding area for a change large enough to digitize that would represent the area's habitat in the dataset as a location affected by hurricane disturbances.

Using the GIS program ArcMap 10.5.1, apparent changes in biological cover of the sea floor were delineated using the post-hurricane image while viewing the data at a scale of approximately 1:4,000 and no closer than 1:1,000. In general, the manual visual survey of post-hurricane imagery focused on scanning for altered shorelines, apparent un-vegetated bottom sediments or areas of high reflectance. Each notable difference or deviation from previous cover was bounded by a polygon and then classified.

Based on the appearance of the surrounding landscape and nature of the change, the delineated features were classified by disturbance types (Table 2). The classification scheme provided a means for describing the physical disturbances visualized and their general sources, to the extent possible. The sources were either: 1) anthropogenic and land-based, or 2) ocean and ecosystem generated and are reflected in the disturbance classes described below. In addition, each delineated polygon was categorized as either "probable hurricane disturbance" or "visible change – possible disturbance." Examples of the later include changes detected in dynamic areas of the marine environment, changes that were indicative of hurricane disturbance but may also be influenced by other more persistent stressors, and locations where delimiting the boundaries of the change were more ambiguous (i.e. along affected shorelines). The central theme for the tendency to categorize disturbances as "visible change – possible disturbance" was the determination of the displayed disturbance as episodic or persistent. If the patterning of disturbance was unclear, the "possible disturbance" was utilized. The possible and probable impact descriptors were applied to qualitatively capture the varying degree of certainty that a reported change was caused by hurricane-specific disturbance activities.

Geoprocessing of the polygon data set occurred after finalizing the rapid imagery review and digitization of disturbances. The GIS-based analysis included calculating the size of the disturbances and intersecting the polygon data (the locations and extents of disturbances) with the best available NOAA benthic habitat maps to identify the habitat types affected by each instance of documented disturbance.

Table 2. Classes applied to features identified and delineated as changes in post-hurricane imagery.

Classification: Disturbance Type	Description
Erosional – Terrestrial	Land-based soil or sediment movement
Erosional	Ocean generated sediment movement
Existing Vessel Scar	Propeller scars new or newly expanded but could not be tied to hurricane events
Sediment Plume	Intense turbidity and suspended sediments
Scar Recovery	Propeller scars visible in pre data no longer visible in post-hurricane data
Shoreline Change	Change in vegetation or contour, scouring, loss of bank stability, sediment deposition
Signature Change	Class within the "Visible Change – possible disturbance" category only, depicting varying degrees of change in habitat, some with changes in level of patchiness (coverage), or the disturbance feature raised questions regarding the feature's reflectance being an artifact of poor image quality and not environmental change
Submerged Debris	Human derived materials, i.e. sunken docks, building materials
Surface Debris	Large mats of (assumed to be) floating plant material, algal blooms
Vessel Scarring	Footprint of visible vessel and/or associated prop scar

Findings

The broad scale seagrass characterization used a suite of five project defined disturbance indicators to direct the effort's rapid imagery review and assessment. Selected indicators were expected to identify key locations where hurricane disturbances would make visible impacts on the environment and potentially seagrass. Some selected indicators in the suite had no predetermined locations for review but targeted natural or photographic features that would exhibit change. A rapid review of imagery compared locations and features of interest in pre- and post- hurricane states then digitized and interpreted any visible changes observed in marine resources. The review resulted in visualizing, delineating, and classifying the extent of only areas of change. The assessment did not complete a full review of Puerto Rico's coastal waters due to missing data or poor clarity within some portions of the available imagery. Data on impacts could not be collected where the sea floor was not visible in the imagery due to issues such as glare, waves, or color balancing. Where the seafloor was visible, the resolution and quality of the imagery allowed for the visualization of both large and small indicators of hurricane disturbance. Scars in seagrass beds from boat propellers or sunken vessels and destruction of coastal roadways and bridges were as easily recognized as well large expansive turbidity plumes cause by the movement of land-based sediments into the marine environment (Figures 1 – 3).

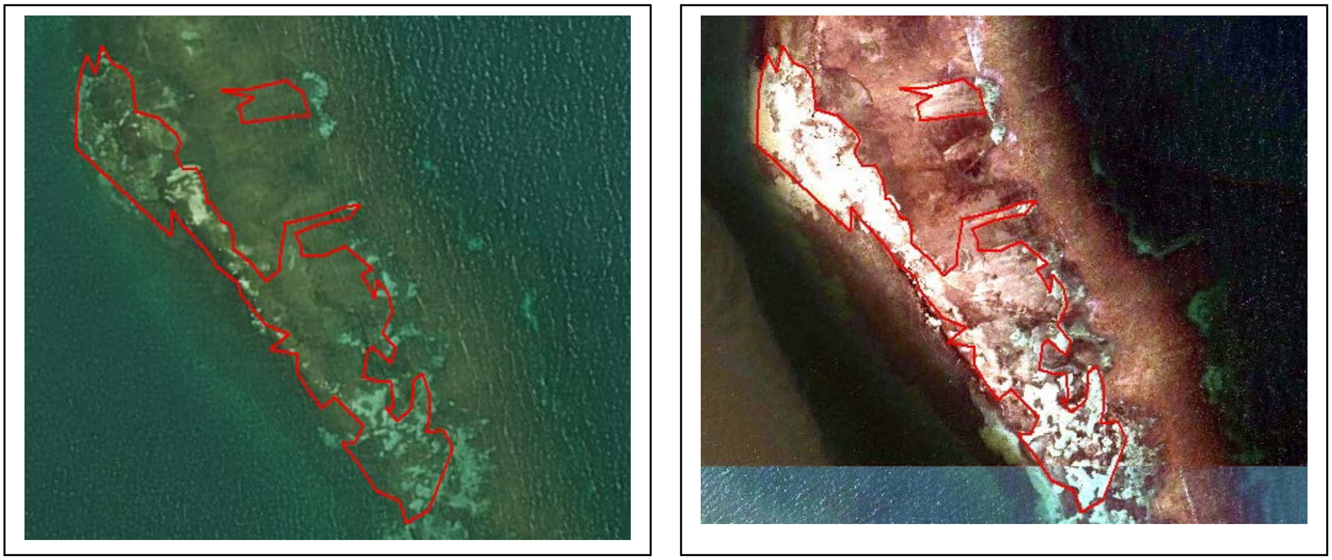

Figure 1. Pre-hurricane imagery (left) and Post-hurricane imagery (right) with red outline of probable hurricane disturbance to seagrass habitat superimposed.

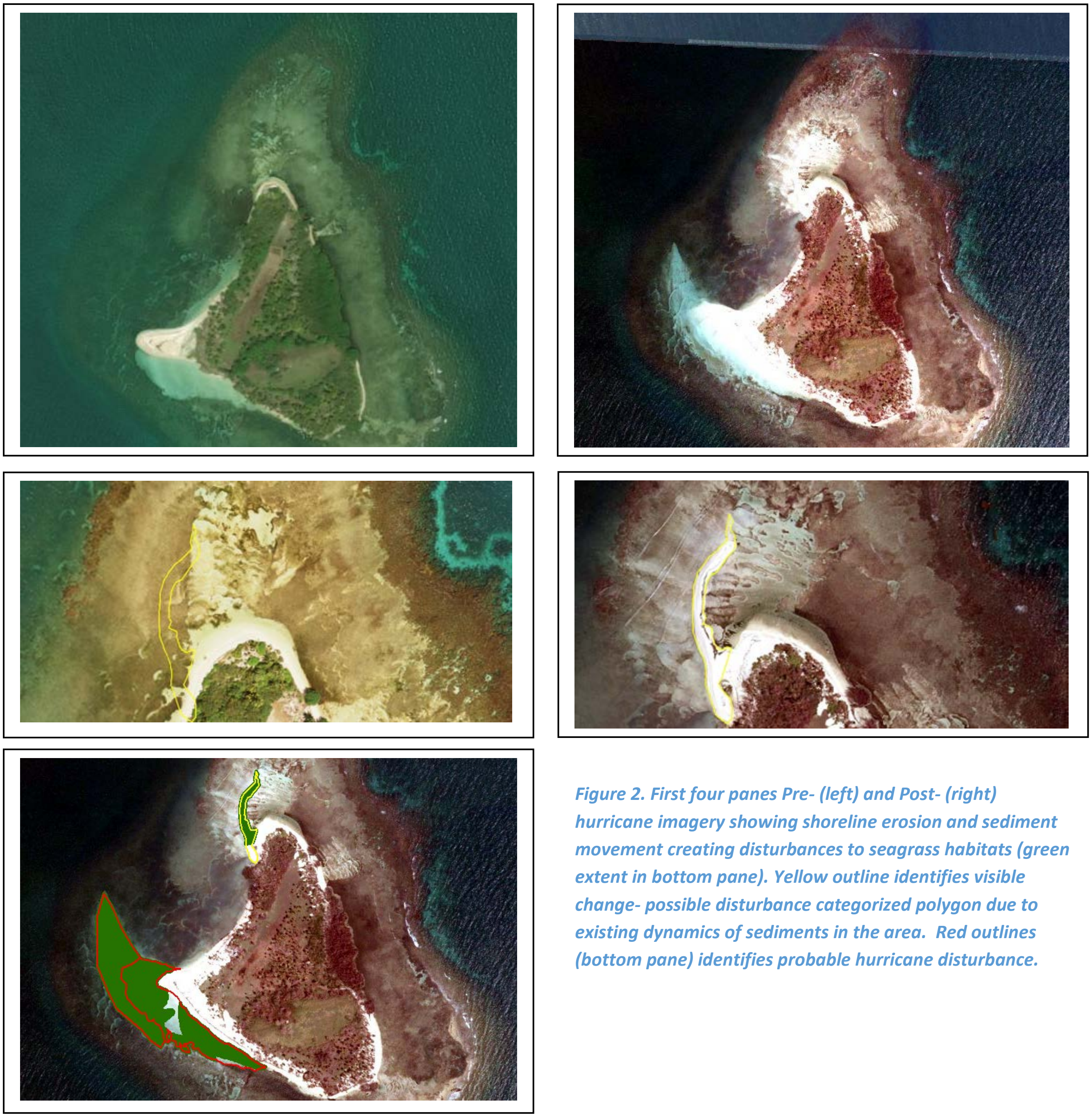

Figure 2. First four panes Pre- (left) and Post- (right) hurricane imagery showing shoreline erosion and sediment movement creating disturbances to seagrass habitats (green extent in bottom pane). Yellow outline identifies visible change- possible disturbance categorized polygon due to existing dynamics of sediments in the area. Red outlines (bottom pane) identifies probable hurricane disturbance.

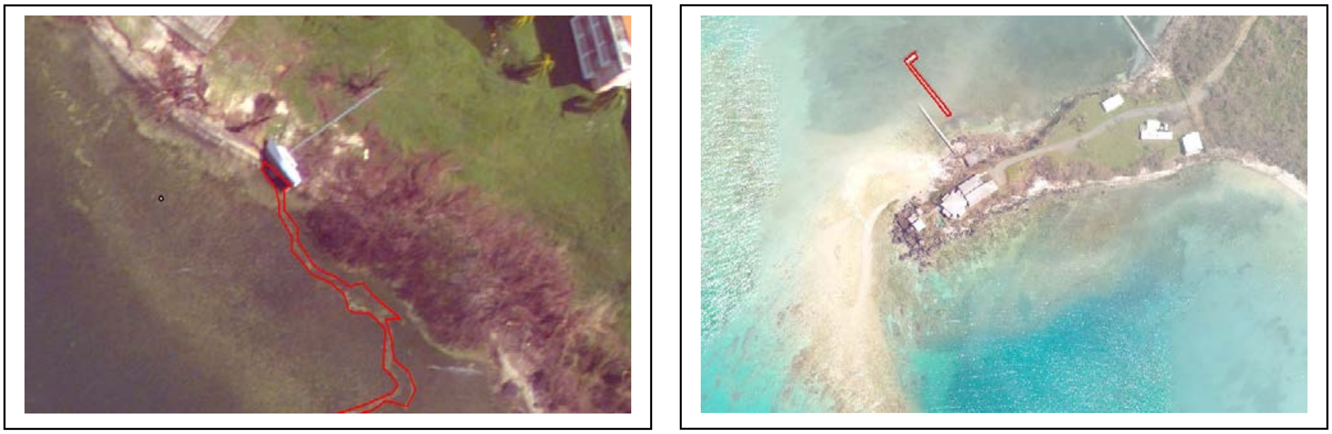

Figure 3. Left pane, delineation of seagrass scar from grounded vessel. Right pane depicts open water-generated turbidity and submerged debris (dock/pier) in Culebra.

Overall, the effort documented 269 instances of change in the seascape after comparing pre- and post-hurricane imagery. Of the 269 total observations, the effort documented three instances of positive change (recovery of seagrass scars) leaving 266 instances of disturbance (Table 3). Two of the disturbance classes captured in the data, Existing Vessel Scar and Scar Recovery, do not represent hurricane-related disturbances. Data under these classes is ancillary information that was collected to assist in locating new potentially vulnerable seagrass resources. Identification of seagrass areas undergoing recovery and those under persistent pressure from boating impacts can highlight areas in need of protection during future seagrass resource management planning. After excluding the data from these two classes, 256 instances of disturbance are categorized as “probable hurricane disturbances” (113 instances) or “visible change – possible hurricane disturbances” (143 instances) (Figure 4). Not all instances documented affected seagrass; however, all instances occurred in locations associated with a marine habitat of importance such as corals, algae, or mangroves (mangrove disturbance only documented if adjacent to a benthic habitat impact).

Table 3. Break out of data collected by disturbance class.

Class	Number of Instances
Erosion – Terrestrial	3
Erosional	131
Existing Vessel Scars	10
Sediment Plume	18
Scar Recovery	3
Shoreline Change	31
Signature Change	17
Submerged Debris	2
Surface Debris	8
Vessel Scarring	46
Total Observations	**269**
Total Disturbances	**266**

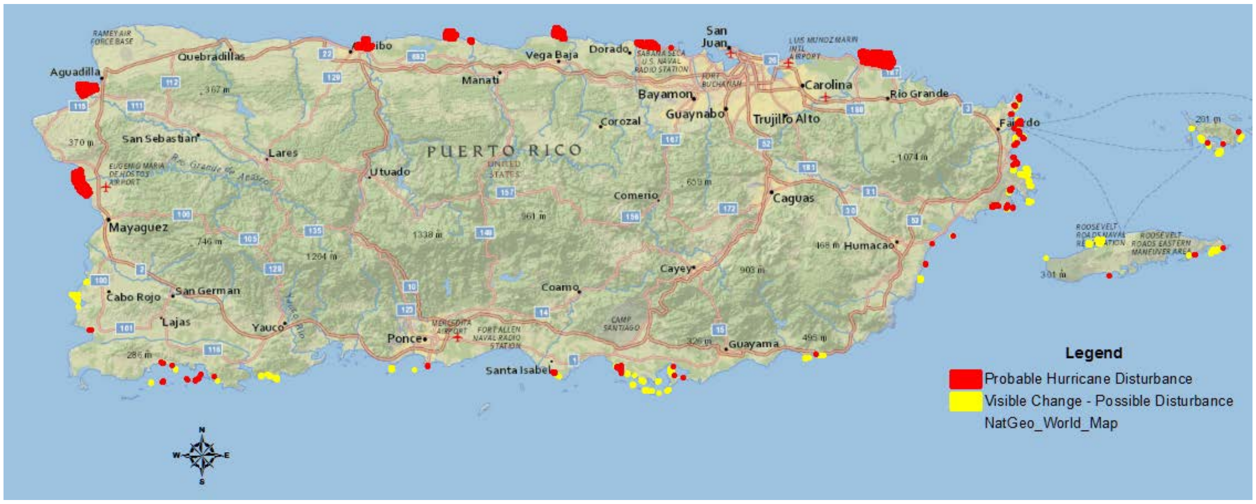

Figure 4. Locations of disturbance detected based on rapid review. Note: individual instances are enhanced to visualize data at this scale.

Geographical Distribution of Disturbances

The 256 instances of disturbance were broadly distributed along the shorelines of 24 municipalities (Figure 5). The municipalities fall into five regions (North, Northeast, Southeast, Southwest, and West) with many of the disturbances clustered around Fajardo, Ceiba, Culebra, and Salinas (Figures 6 – 9). Puerto Rico's natural reserves and other areas identified as being of special concern (Otero et al. 2015, Miller and Lugo 2009) were considered indicators and used to direct assessment review time to vulnerable habitats. Areas under management or protection such as reserves associated with each municipality are displayed in Figures 6 – 9. The freshwater discharge indicator lead the investigation to find a majority of the sediments plumes in the north. The northeast and southeast regions contained the highest concentrations of vessel grounding damages. All other indicators helped locate disturbances distributed throughout the five regions.

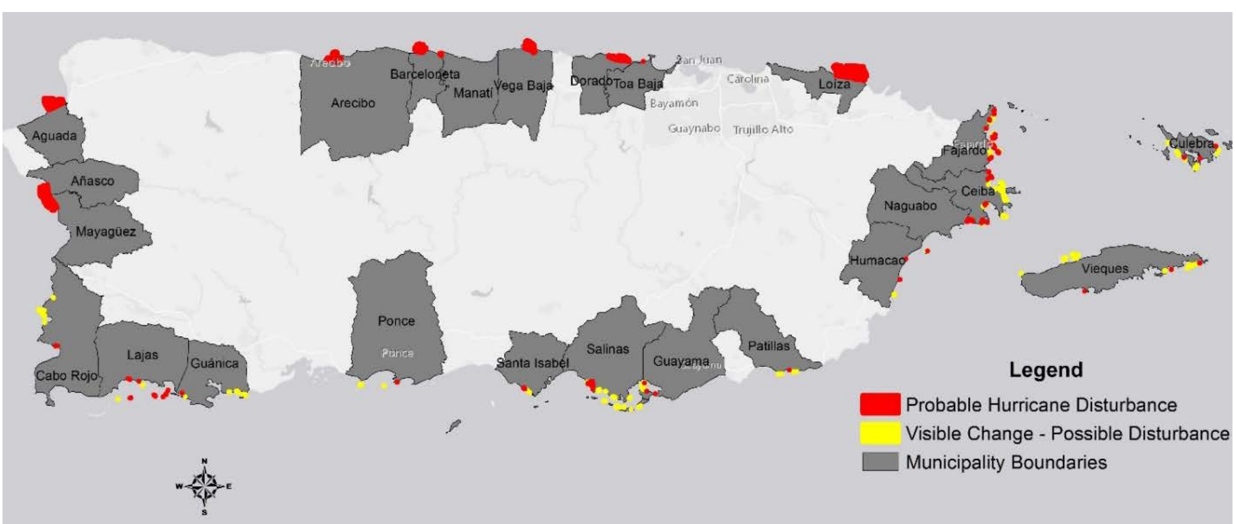

Figure 5. Distribution of disturbances by municipality.

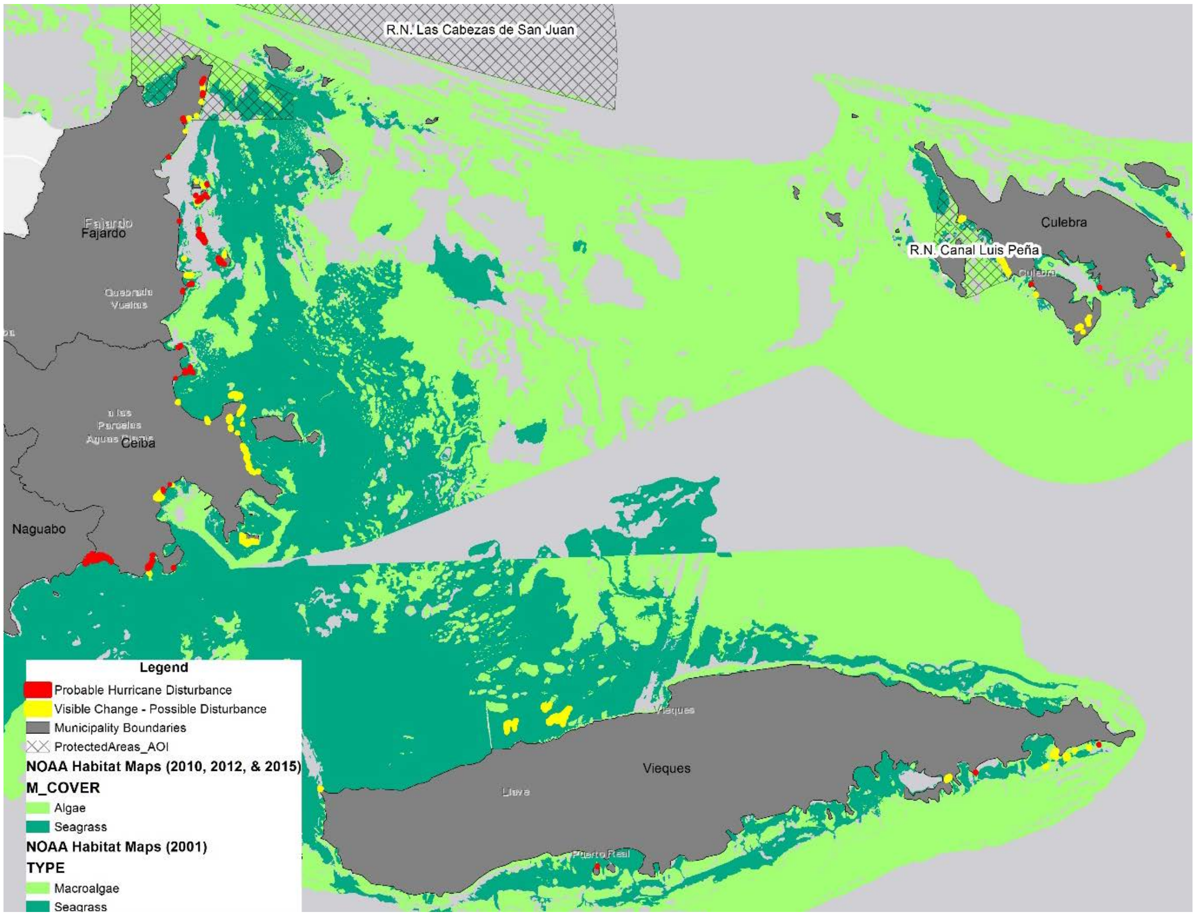

Figure 6. Disturbances within the northeast region. Best available seagrass and algae distribution data are displayed.

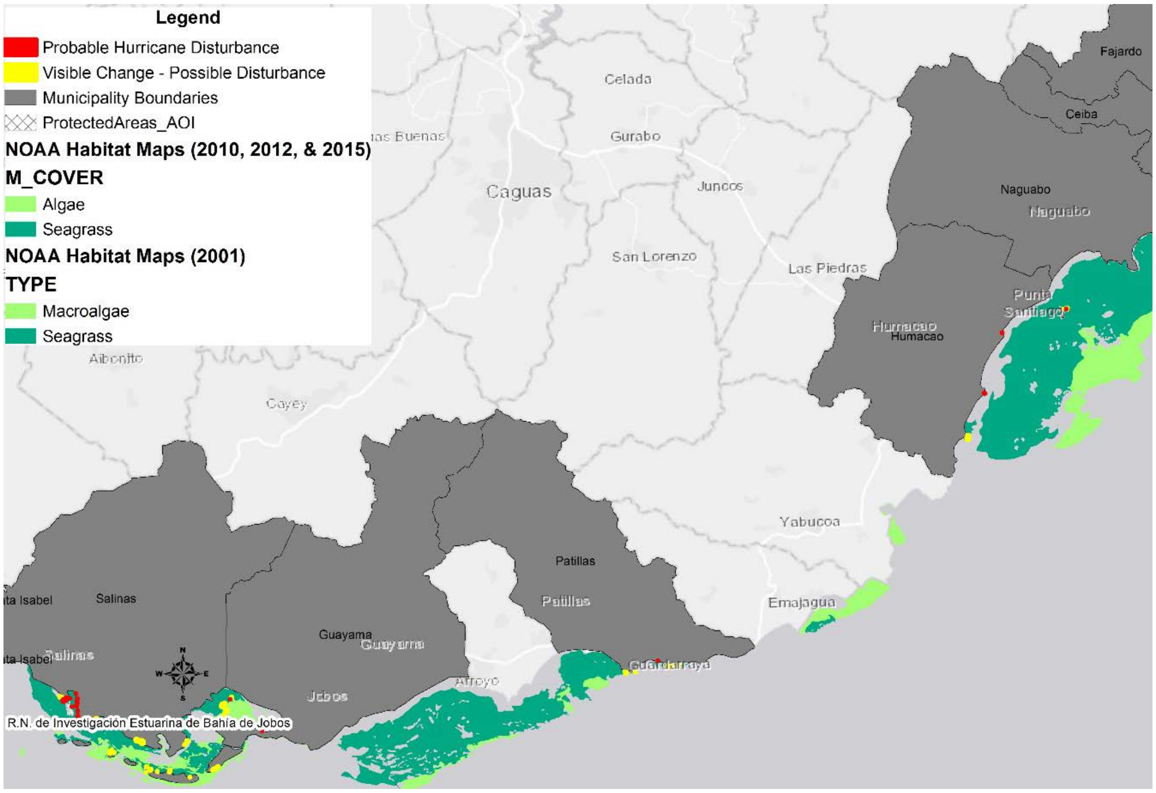

Figure 7. Disturbances within the southeast region

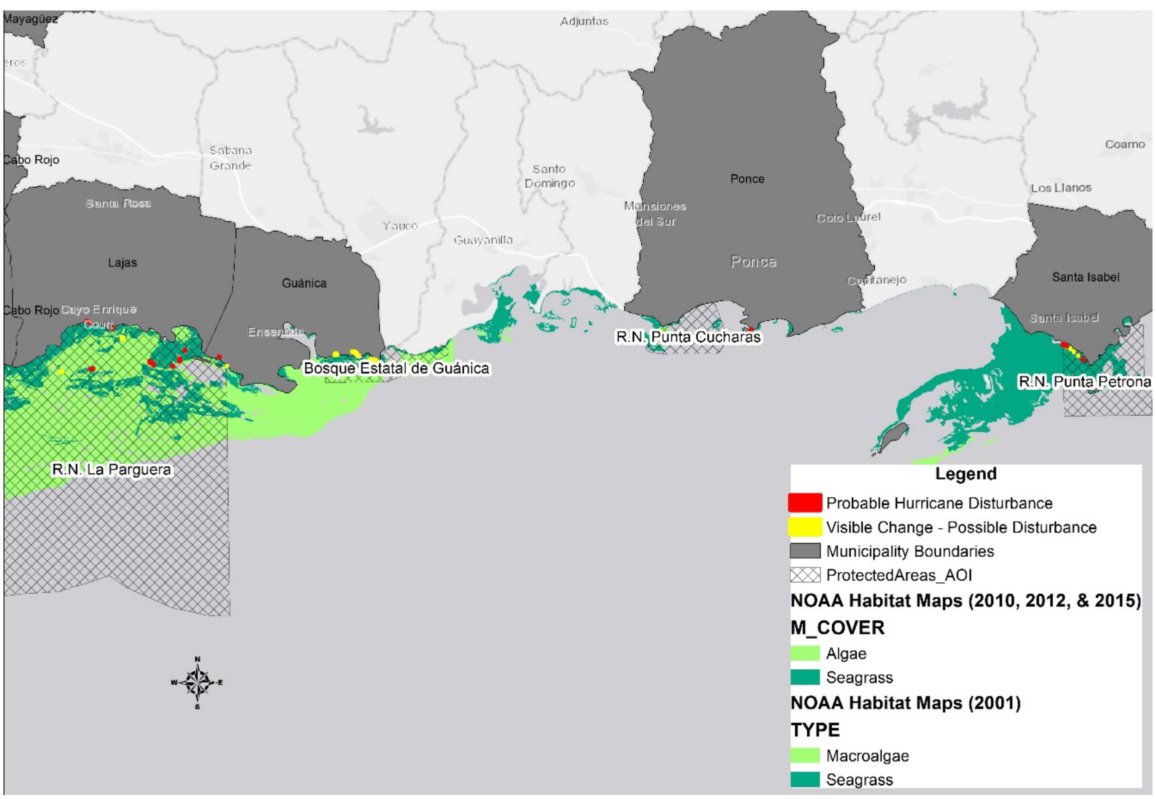

Figure 8. Disturbances within the southwest region.

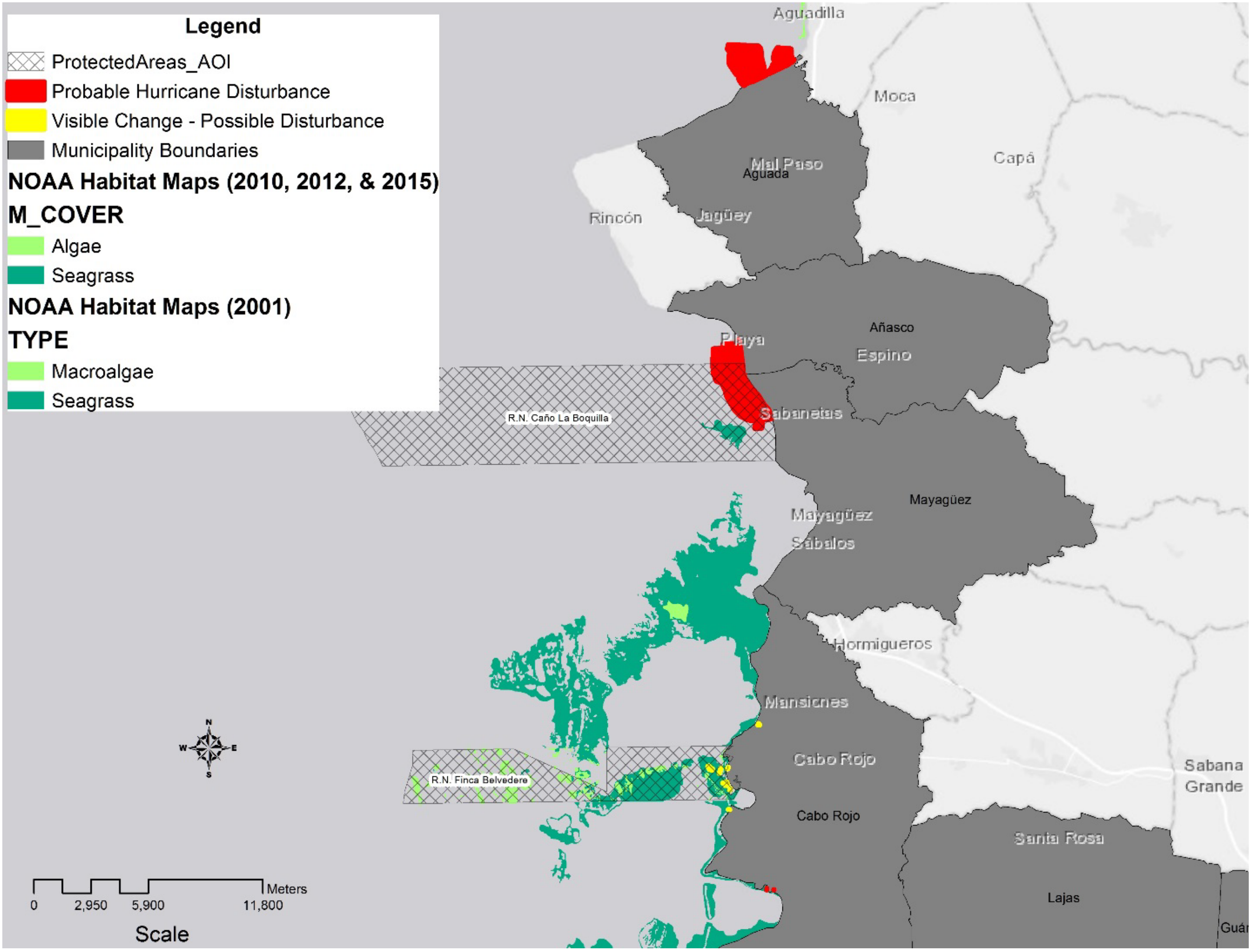

Figure 9. Disturbances within the western region.

Observations of Location-based Indicators

Review of the major freshwater discharge points identified in Table 1, resulted in identification of 16 land-based sediment plumes (Figure 10). The Sediment Plume disturbance class covered the largest areal extent of any disturbance class and potentially exposed multiple habitat types including seagrass, algae, corals, and mangroves to hurricane-related disturbances (Figure 11). Almost all probable disturbances to coral habitats, depicted in Figure 11, correspond to sediment plume disturbances. The remaining plumes, likely generated from open water-based wave or current action, are not associated with a freshwater input.

The available vessel grounding data included locations for 378 vessels, when compared to available habitat maps, 124 were identified in seagrass and 41 were located in mangroves (Figure 12). The coordinates obtained for vessels were not captured directly onboard each vessel resulting in some offset from the actual location, meaning not all initial habitat classifications for the groundings are accurate. After reviewing the locations and conducting quality control, some locations included duplicates, were grounded in habitats other than seagrass, or the vessel was not visible in imagery for delineation. Of the vessel groundings reviewed, 46 were found to be located in portions of seagrass or algal habitats and the boats were visible in the imagery. These disturbances were often associated with locations that have high densities of marinas.

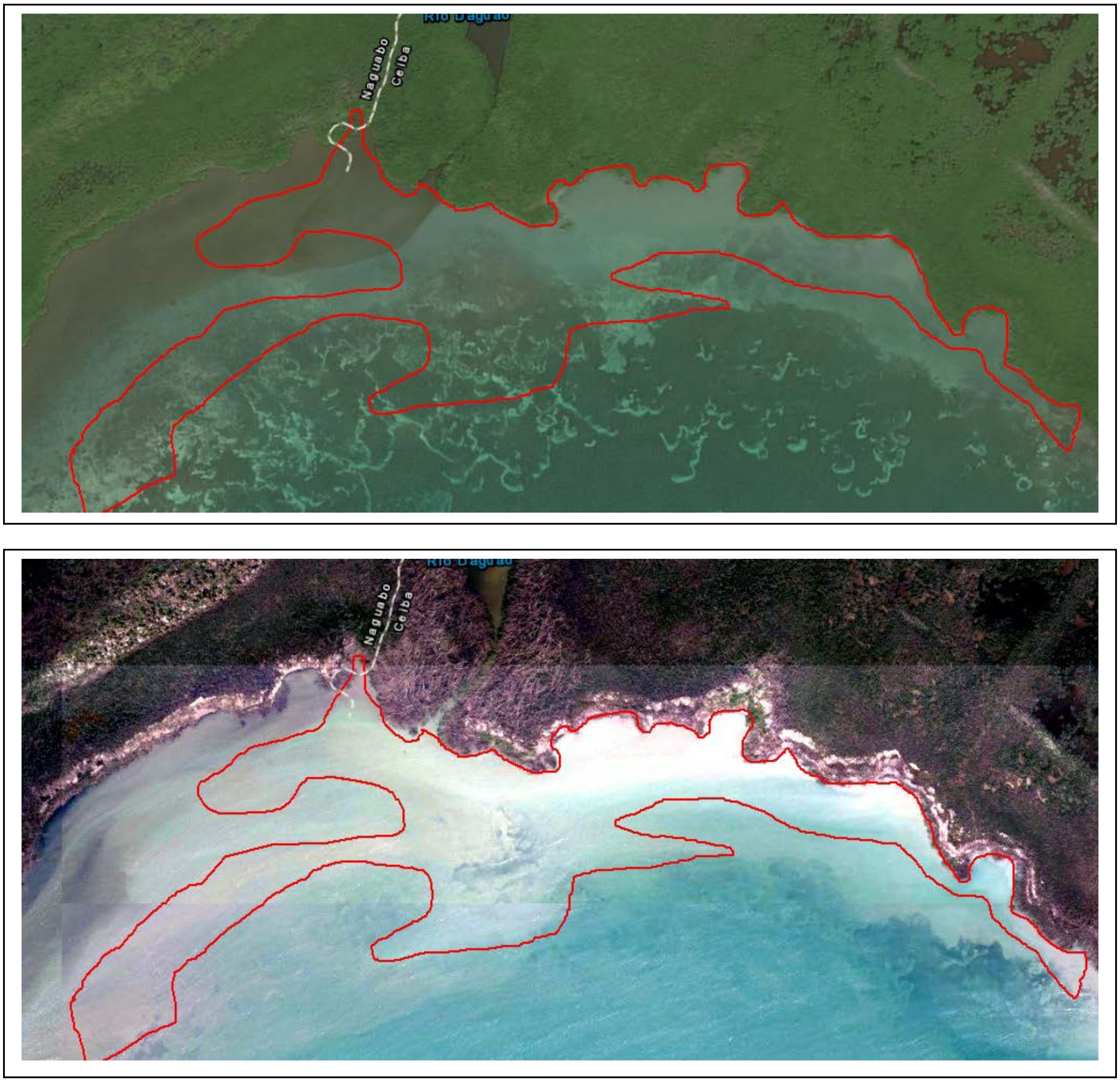

Figure 10. Sediment plume seen as milky white turbidity at the mouth of Rio Daguao. Top pane is pre-hurricane, bottom pane is post-hurricane.

Figure 11. Disturbances by habitat type. Dark green locations are disturbances in seagrass habitats, light green are algae, and purple are disturbances occurring in coral habitats.

Figure 12. Point locations of grounded vessels initially found to be located in seagrass or mangrove habitat. Note: individual point locations were enhanced to view at this scale.

Observations of Feature-based Indicators

The assessment employed two indicators, Eroding Shorelines and High Reflectance Areas Apparent in Post-hurricane Imagery that focused the project's review process on identifying features without predetermined locations. Features indicative of disturbance with characteristic high reflectance included, shorelines adjacent to seagrass habitats, prominent sand features in the seascape, white or bright sand halos around shorelines, island and reef structures, and other areas of unusually high reflectance or sun glint. Features indicative of eroding shorelines included similar references to beaches, shorelines with hurricane-related mangrove damage or those adjacent to seagrass habitats, sand halos around shorelines, and significant changes to positioning of apparent wrack lines when comparing imagery of two time periods. The post-hurricane imagery showed significant destruction of vegetation along shorelines including defoliation and uprooting of mangroves and fallen palm trees. Scouring of shorelines, sand blowouts into adjacent shallow waters and exposure of sediment previously covered by mangrove canopy are visible in the September 2017 imagery.

The rapid review regularly observed changes in bare, sandy features along shorelines as well as changes to bright highly reflective sediments throughout seagrass habitats. Due to time constraints associated with this assessment, delineation of changes to un-vegetated sandy areas within seagrass habitats was limited to documenting "representative" occurrences that were larger in extent, that looked significantly different when compared to the pre-hurricane images, and those that could be seen as representative of the changes for that area. A similar approach was taken when documenting changes to shorelines affected by erosion and sediment movement.

Discussion

This broad scale review completed a preliminary coarse quantification of hurricane related seagrass disturbances within the coastal waters of Puerto Rico. This broad scale characterization of seagrass physical disturbance used a suite of project defined disturbance indicators to detect possible hurricane related effects on seagrass by comparing readily available pre- and post- hurricane imagery.

Results of the rapid assessment approach demonstrated the applicability of GIS interpretative analysis for discerning apparent changes in not only seagrass but also other coastal and marine habitats such as mangroves, algae, and corals. This cursory data can assist with developing and directing additional efforts to conduct in-field assessments of hurricane-related seagrass impacts and to determine the current health of the systems. A more refined seagrass assessment should include additional updates to the NOAA benthic habitat maps, particularly in the South, Southeast, and Vieques.

Many of the disturbance indicators were features showing impacts of sedimentation to the marine ecosystem from various processes and sources. To understand the extent and magnitude of seagrass disturbance additional in-field data collection is required. The level of impact to a seagrass habitat due sedimentation depends on the amount of sediment deposited and the length of time plants remain buried (Koch et al. 2006, Tilmant et al. 1994).

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