Coastal Erosion as a Function of Sea Level Rise and Sediment Imbalance

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Abstract *– This study analyses the effects of coastal erosion in the city of Loíza, Puerto Rico, and how does the Carraízo Dam located at Trujillo Alto, Puerto Rico contributes to the sediment imbalance along the Loíza coast. The study centers on evaluating the hydrological impacts of anthropogenic disruption to the natural fluvial sediment transport dynamics, with emphasis on the alterations to the alluvial system and hydro morphological processes of the Río Grande of Loíza, resulting from the construction of the Carraízo Dam. Despite extensive research on mitigating coastal erosion, few studies have directly attributed shoreline degradation to dam construction. By analyzing the physical changes of the river using high-resolution bathymetric data and satellite imagery interpretation we can get preliminary results suggesting a correlation between coastal erosion and sediment imbalance cause by the Carraízo Dam high efficiency sediment retention. The reduction in sediment discharge not only accelerated shoreline retreat but also it exposed the riverbed material downstream, affecting the environment, communities, and families that live in nearby areas and on the coast of the Loíza municipality.*

Key Terms *– Coastal Erosion, Carraízo Dam, Sediment Transportation, Bathymetric Data, Satellite Imagery, Anthropogenic Disruption.*

INTRODUCTION

Climate change remains one of the most significant global challenges, leading to long-term shifts in temperature and weather patterns with far-reaching consequences for public health, food security, infrastructure, employment, and social stability. Although climate change impacts countries worldwide, small islands and nations such as Puerto Rico experience elevated vulnerability due to their geographical limitations, economic challenges, and constrained capacity to adapt effectively. Some of the challenges like rising sea levels, coastal erosion and increasingly extreme weather events are threatening coastal communities and vital ecosystems that sustain economic stability. The reasons behind the causes of coastal erosion in Puerto Rico stem from natural factors and anthropogenic disruption, including deforestation, urbanization, dam construction and other infrastructure development. This erosion results in the loss of beaches, destruction of habitats, and significant risks to essential infrastructure like roads, housing, and sewer systems.

The sedimentation on water bodies like the Río Grande of Loíza is a natural process of the effects of climate and the physiography of watersheds. All basins are subject to erosion due to the effects of wind and rain on the distinct types of soils on the ground surface. Eroded soils are primarily washed away by runoff resulting from rainfall that does not evaporate or infiltrate the soils. This sediment transport occurs in a "laminar" (dispersed over the ground) or turbulent form in the channels of streams and rivers, from the elevated areas to the lower ones. This process has been going on for hundreds of millions of years since the emergence of the Puerto Rico shelf on the ancient seas in the Greater Antilles. The Alluvial Valleys in the four coastal provinces of Puerto Rico were formed from soil eroded primarily by rainfall in the Mountainous Interior Province, which were then washed away by runoff from rivers flowing from this province to the coasts. Therefore, the Carraízo dam is causing a natural disruption leading to deficiency on the sediments that get to the coastal area of Loíza. Since the construction of the dams that form the reservoirs, they have been retaining 70 to 95 percent of the sediments they receive [1].

Figure 1
Main Reservoirs in Puerto Rico

LITERATURE REVIEW

Reservoirs and Sediment Transportation

The subsequent section will provide a comprehensive review of the literature. Dams are a unique type of infrastructure in that the commodity they produce, a regulated water supply, tends to increase in value with time as water supplies become increasingly scarce relative to demand. The importance to society of today's reservoirs can be expected to increase over time as population, economic activity, and irrigation demand grows. While modern hydraulic systems consist of many elements to appropriate both surface and groundwater supplies, in many regions reservoirs are the single most important component. However, uncontrolled sediment accumulation makes storage reservoirs the key non-sustainable component of modern water supply systems. The twenty-first century has been characterized by increasing water scarcity in response to continued population and economic growth.

All rivers transport sediment as well as water, and dam construction impacts the transport of both substances but with significant differences. Because rivers transport much more water than sediment it takes much longer to fill a reservoir with sediment than with water, so much more that the gradual accumulation of sediment tends to be ignored. Most sediments accumulate underwater where it is not visible further removes the problem from popular, political, and engineering consciousness. But the most significant difference is this: water can be easily removed from a reservoir, but sediment cannot. As reservoirs age, the impacts of sedimentation are becoming more severe and better recognized, and the frequency and severity of sediment-related problems are increasing.

The Carraízo dam was originally constructed in 1953 it has height of 98 ft and it's 689 ft long with a storage capacity of 26.8 million m^3. Due to sediment buildup, the dam's capacity has decreased to 12.4 million m^3 as of December 31, 2021, with 14.4 million m^3 of sediments present. Severe flood events, such as Hurricane María, can have a substantial impact on reservoir capacity. For instance, Hurricane María introduced approximately 2.6 million m^3 of suspended solids, reducing the Carraízo reservoir's storage capacity by 13 percent, a loss equivalent to six years of typical sediment deposition. Downstream of the Carraízo dam, the riverbed is noticeably exposed due to a reduced sediment supply, as a direct result of the dam's retaining capability.

On the other hand, a study conducted by Jonathan A. Warrick, Andrew W. Stevens, Ian M. Miller, Shawn R. Harrison, Andrew C. Ritchie & Guy Gelfenbaum presented the Elwha and Glines Canyon dams from the Elwha River had the same effects as the Carraízo dam on the morphology of the river and the rate of change in the fluvial and coastal landforms [2]. Elwha River dams have three times the storage capacity of Carraízos dam. The Elwha dam was constructed in 1913, had a height of 104 ft and a storage capacity of 10.0 million m^3. The Glines Canyon dam was constructed in 1927, had a height of 209 ft and a storage capacity of 50.0 million m^3 [3]. Approximately 11.1 million m^3 of sediment were deposited in the river's reservoirs before the dam's removal in 2011. The grain size of these reservoir sediments was found to be approximately 63% coarse (sand, gravel and cobble) and 37% silt and clay by mass. Sediment capture by the reservoirs resulted in downstream reductions in sediment supply that caused measurable coarsening of the riverbed to an armored, cobble substrate.

Figure 2
Exposed Riverbed Downstream Carraízo Dam

Loíza Puerto Rico Coastal Erosion

Loíza has a population of 23,693, as per the 2020 census, with the highest population density found in coastal wards. Loíza coastal length is 21.27 km and has a beach length of 17.58 km consisting of 83 percent of beach length [4]. Medianía Baja, the largest coastal ward, houses 6,826 people, followed by Medianía Alta, Pueblo, and Torrecillas Baja. These coastal areas are particularly vulnerable to the combined threats of sea level rise and coastal erosion, with Medianía Baja, home to the largest population, facing the greatest risk. Within this ward, the community of Parcelas Suárez is at heightened risk, particularly for the homes directly across from the beach, which remain unprotected by the revetment. Currently, only 10 families still reside in the area. The communities of Las Carreras and Los Lucas in Medianía Alta are also facing similar threats from the encroaching coastline. This background sets the stage for understanding the challenges Loíza faces, particularly in how its population, coastal areas, and ecosystems are impacted by climate change, necessitating urgent policy intervention and action.

Costal erosion and shoreline changes have been caused by many factors around the island of Puerto Rico. Some factors are: 1) the variability in physical parameters such as waves, storms and floods, 2) the variability in shelf morphology, 3) the availability of sand deposits in the nearshore area, 4) beach location and orientation, 5) human activities and 6) the presence of submarine canyons. A study from Maritza Barreto-Orta suggests that the main sand loss in the North coast of Puerto Rico was from 1964 to 1987. This erosion could be related to the occurrence of high amplitude waves generated by extratropical and tropical cyclones systems, human activities such as construction of dams and sand extraction. Between 1961 and 1971, most beaches experienced the highest erosion rates due to high amplitude waves from the north and northwest, as recorded by WIS data. From 1971 to 1975 waves approached from the North and Northeast (0 – 65 degrees) reporting the presence of lower amplitude waves that caused the reduction in erosion rates in the North part of the island. The construction of breakwaters, docks, and water reservoirs could have caused a major reduction of sediment input to the beaches. The coastal structures appear to have produced new local current circulation on the nearshore that had generated sand transport toward offshore. The Loíza municipality has a shoreline change rate of erosion of -1.93 m/yr utilizing a data from 1970 to 2010 [4]. The coastline retreat can be observed on Figure 3.

Addressing the challenges of coastal erosion in Loíza is critical to ensure the resilience of its communities, preserving its ecological integrity, and securing the livelihoods of future generations. Without urgent action, the continued loss of land and infrastructure will exacerbate social and economic vulnerabilities, making intervention a pressing necessity.

Figure 3
Rate of Change Río Grande of Loíza 1901 to 2018

Study Area

Loíza is located in the Northeast area of Puerto Rico (18.431ºN, -65.876ºW), which comprises an area of 19.4 m^2. Loíza is characterized by its coastal plain, to the North it has the Atlantic Ocean, to the South the municipality of Canóvanas, to the East the municipality of Rio Grande and to the West the municipality of Carolina. Loíza consists of a mangrove vegetation because of the Piñones State Forest and the Piñones Lagoon. Loíza belongs to the Northern Alluvial Coastal Plain and it's located in the karst zone. For this reason, it is characterized by its caves, mogotes, sinkholes and aquifers. The surficial deposits of Quaternary age cover the Tertiary age formations in the northern part of the region. These surficial deposits consist of alluvial deposits, blanket sands, beach and dune sands, and swamp deposits as represented in Figure 4. The municipality is organized into the following wards: Canóvanas, Loíza Aldea, Medianía Alta, Medianía Baja, Torrecilla Alta, and Torrecilla Baja.

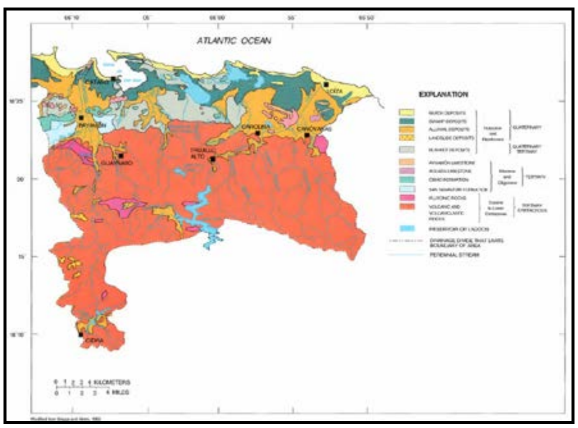

Figure 4
Generalized Surficial Geology in the Bayamón-Loíza Region, Puerto Rico [1]

The Río Grande of Loíza and its tributary rivers: the Caguitas, Bairoa, Cañas, Gurabo and Quebrada Infierno rivers mainly supply water to the Carraízo dam. The reservoir occupies an area of approximately 1,000 acres of land in the Carraízo and La Gloria neighbourhoods of Trujillo Alto, Celada and Rincón de Gurabo, as well as San Antonio, Río Cañas and Bairoa de Caguas. Its area is 421.7 hectares with an average depth of 27.88 ft and a maximum depth of 96.78 ft. This is the largest reservoir in Puerto Rico in terms of drainage area, spanning 533 km^2. Its main function is to provide drinking water to the metropolitan area of San Juan, and its catchment basin covers an area of 797 km^2. The Río Grande of Loíza discharges its water to the Atlantic Ocean passing through the Loíza municipality.

METHODOLOGY

This section outlines the procedures, tools and data used to analyze the sediment imbalance and erosion rate on the Loíza municipality coast. Bathymetric data reports, satellite imagery, Environmental System Research Institute data from the USGS, CARICOOS database, and both short-term and long-term rates along the North coast shoreline were utilized for this assessment. The first evaluation focuses on identifying the Loíza coast depth and the Carraízo dams available capacity. The second evaluation permits to analyze the erosion rate on the Loíza municipality coast and assess the rate of change, both long-term and short-term on the northern coast of Puerto Rico. The third evaluation identifies the wave patterns and intensity impacting coastal areas and assesses their effect on coastal erosion.

Bathymetric Reports

A method of survey and analysis was done in October of 2019 for the Lago of Loíza. Before this survey two others were performed on 2004 and 2009 and the procedures where establish by CWSC and described in the previous bathymetric survey report for Lago Loíza [1]. The 2009 field data for the survey was collected using a Survey Case-200S bathymetric survey system, manufactured by Specialty Devices Inc. The system included an onboard computer, depth sounder (200 kHz), and GPS system. The computer included the SMARTSURVEY navigation software and DEPTHPIC software for data collection and post processing. The survey was performed using a boat onto which the GPS–SONAR system was mounted, and the collected data were post-processed later in an office with AutoCAD as X-Y-Z text files. The complete dataset was used to create a DEM (digital elevation map) within the AutoCAD Civil 3D environment, National Centers for Environmental Information [2]. The DEM was subsequently processed to prepare contour maps of elevation and then exported to ARC-GIS for subsequent data processing and calculations. Transducer calibration to the speed of sound in the water column was performed at the beginning of each survey day and again at noon using the technique for deep manual probing recommended by the U.S. Army Corps of Engineers.

The NOAA Data Access Viewer uses sonar for multibeam bathymetry to create high-resolution seafloor images, and aircraft-mounted LiDAR sensors to measure shallow water depths. The collected data produces a digital elevation model, useful for creating elevation maps that can explain coastline behavior.

USGS Shoreline Imagery

The Coastal and Marine Hazards and Resources Program of the United States Geological Survey (USGS) has been utilized to analyze the historical coastal changes at the Puerto Rico coastline and the United States [5]. Using aerial photographs, high resolution satellite images, LiDAR (Light Detection and Ranging) data, and historical maps. The program has created a database of Puerto Ricos shoreline positions from 1901 to 2018 that helps understand the shoreline behavior.

WCA Model Point Output

The Caribbean Coastal Ocean Observing System (CARICOOS) brings together coastal ocean data and forecast from a variety of sources including satellites, ocean instruments and numerical models to give the user an integrated view of past, present and forecasted ocean conditions in the US Caribbean region [6]. The WCA model point output is a web interface with time series data and graphical products are provided at buoy locations and points along the 20 m and 100 m depth contours. The model provides time series of wave parameters such as height, period and direction, generating directional wave rose plots with data collected from 1979 to 2018.

RESULTS

In the next section, the results of bathymetrical reports, USGS imagery and WCA model point output will be discussed.

Bathymetrical Reports

The bathymetrical data refers to the information on the depths and topography of lakes. In this instance, bathymetrical data from the Loíza Lake has been gathered. On Figure 5, you can find the storage volume in million m^3 in reference to the mean sea level elevation of the Loíza Lake for the years 2004, 2009 and 2019. The storage capacity for 2004 was 17.53 million m^3, 16.42 million m^3 in 2009 and 15.06 million m^3 in 2019.

Elevation	2004	2009	2019	Elevation	2004	2009	2019
(m-msl)	Storage Volume (Mm^3)			(m-msl)	Storage Volume (Mm^3)		
26.14	0.00	0.01	0.00	34.14	4.76	3.88	3.02
27.14	0.03	0.01	0.00	35.14	5.90	5.01	4.08
28.14	0.25	0.08	0.07	36.14	7.31	6.36	5.38
29.14	0.76	0.31	0.22	37.14	8.95	8.00	6.90
30.14	1.41	0.74	0.50	38.14	10.80	9.83	8.63
31.14	2.12	1.32	0.91	39.14	12.84	11.85	10.55
32.14	2.91	2.06	1.47	40.14	15.07	14.05	12.71
33.14	3.78	2.91	2.17	41.14	17.53	16.42	**15.06**

Figure 5

Lago Loíza Stage Storage Data Presented for Survey Years 2004, 2009, and 2019 [7]

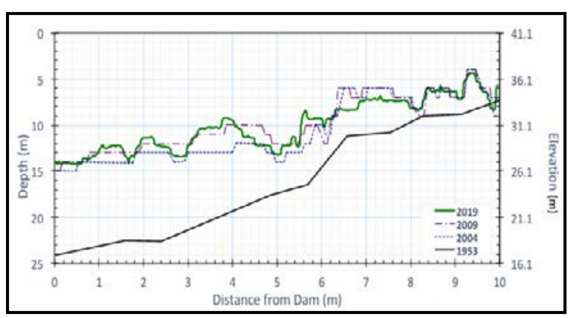

Figure 6

Bathymetric Profile of Lago Loíza for the Last Three Surveys and Compared to the 1953 Pre-Impoundment Profile [7]

Based on the bathymetrical data, a cross-section of the Loíza Lake has been illustrated in Figure 6. The cross section presents bathymetrical report data from the years 2004, 2009, and 2019 for comparison.

Based on the bathymetrical report of 2019 a digital elevation model of the Loíza Lake was developed and illustrated in Figure 7. It represents the depth of the lake in reference to the mean sea level.

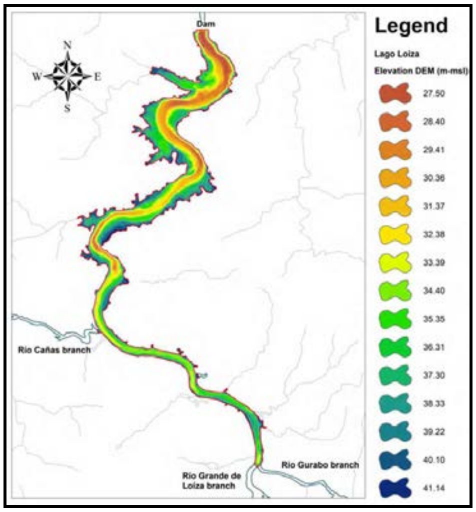

Figure 7
Lago of Loíza DEM Map Developed from Bathymetric Survey Data of October 2019 [7]

From the NOAA ATLAS Access Viewerdata base, a LiDAR image has been downloaded to QGIS to develop a bathymetric imagery of the Parcelas Suárez representing the depths of the Loíza coastline.

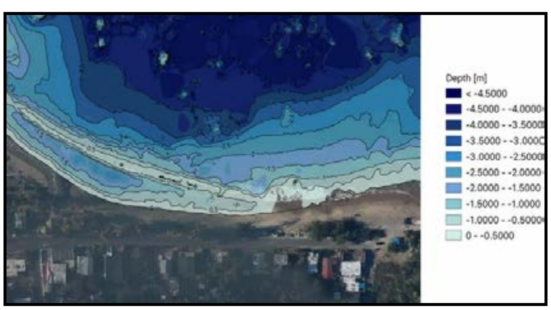

Figure 8
Bathymetry Data of Parcelas Suárez [8]

USGS Shoreline Imagery

In Figure 9, the coastline behavior has been represented with the USGS data that has been recollected from 1901 to 2018. Significant changes in the coastline over the years are clearly observable.

Figure 9
Coastline Behavior of Río Grande of Loíza, 1901 to 2018 [8]

Figure 10 illustrates the North of the island coastline change of rate measured by meters per year. Values above zero represent accreditation and below zero the erosion of the coastline.

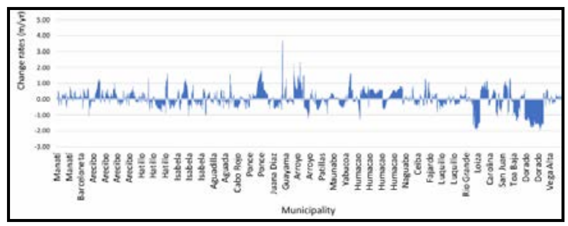

Figure 10
Shoreline Change Rate (m/yr) from 1970 to 2010

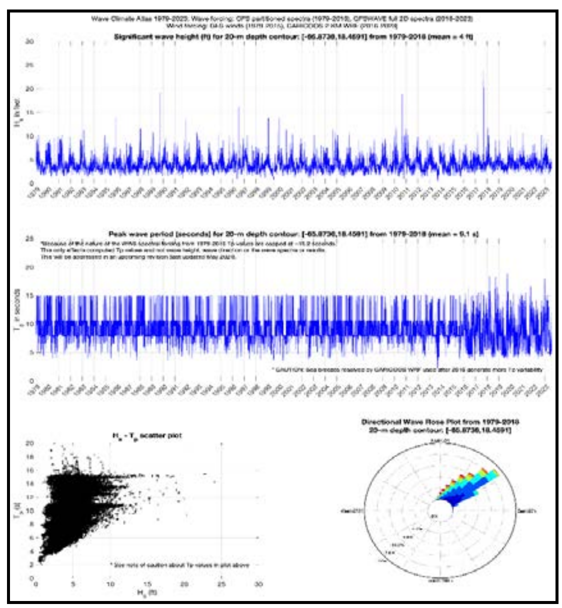

Figure 11
Depth Contour at 20 m for a 40-Year, Time Series Plot and 40-Year Wave Rose Plot

WCA Model Point Output

The Caribbean Coastal Ocean Observing System has data from 1979 to 2025. From a buoy with a 20 m depth contour the height of the waves, periods in seconds and wave direction can be determined.

DISCUSSION

The focus of the study is to analyze the erosion effect on the Loíza coast and how the Carraízo dam contributes to the sediment imbalance. There are many factors that contribute to the erosion rate at the Loíza coastline. The retention rate of a dam in Puerto Rico varies from 70 to 95 percent of the sediments that they receive. That means that much of the sediment that the river transports get retained at the dam and does not get to the coastline. Let's remember that the alluvial valleys in the four coastal provinces of Puerto Rico were formed from soil eroded primarily by rainfall in the Mountainous Interior Providence. During high rain events, floodings or natural disasters like hurricanes the suspended sediments are dragged on the river stream and the "plumaches" into the main river and coast are visible. On the bathymetric reports, Figure 5 demonstrates that the Carraízo dam reduced its capacity by 11.75 million m3 in 2019. The Water Resources page of Dr. Ferdinan Quiñones reports that as of December 31, 2022, the capacity has decreased by 13.67 million m³, which represents 51 percent of total capacity. Figure 6 illustrates the cross section of the river, highlighting the retaining factor of the dam that serves as a barrier for accumulating river sediments over the years.

Because river mouths and deltas are inherently dynamic landforms from the variability of river sediment supply with time as well as other hydrologic and oceanic factors, erosion of these systems can be pronounced where sediment is intercepted by dams. A research study involving the Elwha and Glines Canyon dams on the Elwha River revealed the presence of 11.1 million m^3 of sediment. The sediments that were trapped on the reservoir were the cause of the measurable changes in morphology and rates of change in the fluvial and coastal landforms. In 2011, the removal of dams on the Elwha River was the largest project of its kind at that time, resulting in the greatest sediment release from a dam removal.

The shoreline image in figure 9 illustrates the coastline's expansion, impacting communities such as Parcelas Suárez in the Loíza municipality. Figure 10, illustrates that the erosion factor on the Loíza coast is one of the largest -1.93 m/yr, then Arecibo follows with -1.04 m/yr, and we have the Manatí showing ± 0.5 m/yr. A comparison of these three municipalities reveals a significant difference as you can see in Figure 12. Arecibo and Loíza have dams that hinder sediment transportation to their coastlines, while Manatí does not have a dam blocking the sediment flow of Río Grande of Manatí, thus defining it as a stable or unaffected area by the erosion.

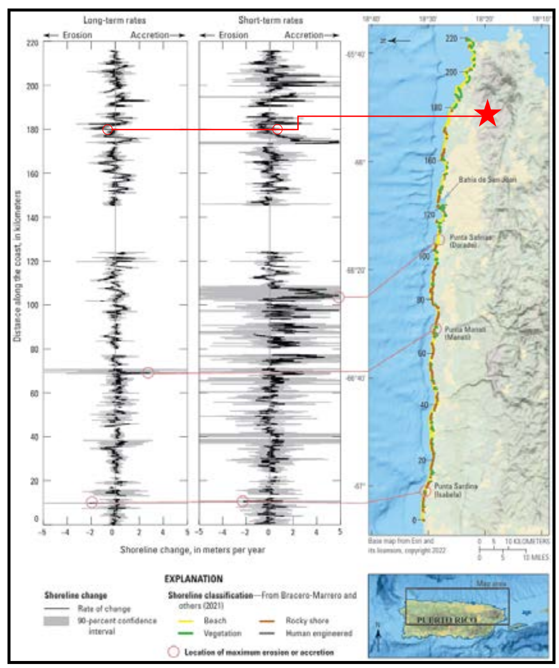

Figure 12
Long-Term 1900 to 2018 and Short-Term 1970 to 2018 Shoreline Change Rate Along the North Region of Puerto Rico

At the river delta on the Elwha River study, reduced sediment supplies resulted in shoreline erosion that average 0.6 m/yr during the 20th century and increased significantly over this time.

The delta restauration on the Elwha River coast due to the dam removal had restored the natural sources of sediment to the coastal system and the potential to build landmasses and reduce coastal hazards. The Elwha River coastal system responded rapidly to the reintroduction of millions of tons of sediment formerly stored within its reservoirs. The coastal morphodynamical response was initiated with submarine lobes of coarse sediment deposited at the river mouth, the upper portions of which were reworked by ocean swell and wind waves during the pending months to years into subaerial river mouth bars as illustrated on Figure 13.

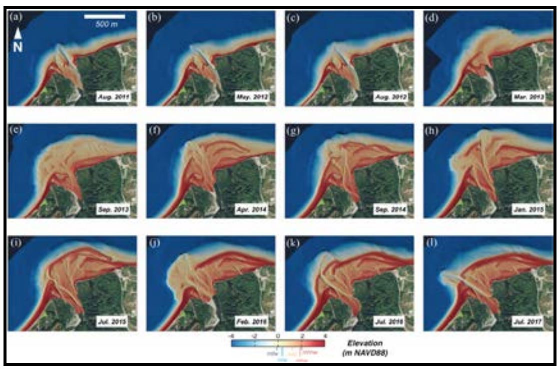

Figure 13

Restoration of the Elwha River Delta Topography and Bathymetry Before, During, and After Dam Removal, 2011 to 2017 [9]

The Atlantic Ocean wave pattern significantly influences coastal erosion in Loíza. Particularly when the waves originate from the northern or northwestern direction. Figure 11 shows the directional wave rose plot at a depth of 20 meters, indicating that 5.6 percent of the waves originate from the northwest with heights of up to 2.74 m. Although waves from the northwest are less frequent compared to those from the northeast, their impact on the coast is significantly greater. Waves from the northeast account for 27 percent of occurrences, with wave heights of 1.52 m or less. For the North coast, the highest short period waves were found from May to October and long period waves occurred from October to December. Strong wave action leads to the removal of beach sediments, causing the shoreline to retreat.

CONCLUSIONS

Erosion and climate change pose ongoing challenges for Loíza's coast and Puerto Rico. To support affected communities, strategies must be implemented to protect roads, hospitals, water treatment plants, and other facilities from rising sea levels. Some strategies can be implemented to mitigate coastal erosion and sediment imbalance at the coast area: 1) **Coastal resilience**: coral reefs, mangroves, and coastal dunes serve as natural barriers absorbing wave energy, protecting shorelines from storm surges, and helping protect inland areas from erosion and flooding. This is a nature solution to help mitigate coastal erosion. 2) **Dam removal**: Dam removals have been successful transporting all the sediments that were retained and had help with the restoration of the delta topography and shoreline recovery. 3) **Construction of out of channel reservoir**: The implementation of reservoirs that are out of course can help keep the sediment downstream and into the shoreline. These reservoirs are fed by an intake in the river and a conveyance pipe, whose hydraulic capacity is typically less than 1 percent which prevents a significant fraction of the flood sediment from entering the reservoir. In contrast, all the sediment enters the conventional reservoir, and more than 90 percent of sediment gets trapped in it. An additional approach is an effective method to address dam removals while ensuring a continuous water supply for the community. 4) **Reef balls**: Reef balls fall under the disciplines of coastal and environmental engineering, as they serve as a nature-based solution to mitigate shoreline erosion while supporting marine biodiversity. Additionally, they align with ecological engineering principles by integrating artificial reef structures with natural processes to promote habitat restoration. Their design helps dissipate wave energy, reducing coastal erosion, which further stabilizes the shoreline [7].

The removal of the Carraízo dam may assist in restoring the shoreline in the Loíza municipality. Additionally, constructing an off-channel reservoir to maintain the water supply and reduce the sediment that gets trapped would help reverse the anthropogenic disruption that has been caused.

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