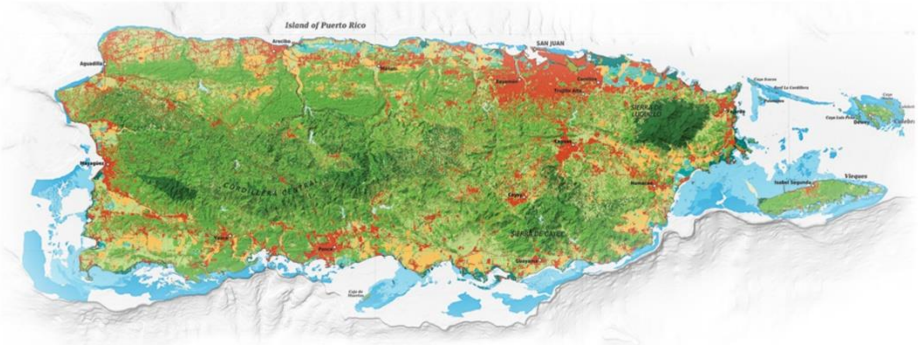
COASTAL ENGINEERING HANDBOOK

Best Practices for Puerto Rico



Presented to:
Department of Natural and Environmental Resources
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Acronym	Description
CZMA	Coastal Zone Management Act
DNER	Department of Natural and Environmental Resources
PR	Puerto Rico
PRCZMP	Puerto Rico Coastal Zone Management Program

1 INTRODUCTION

1.1. Background

The Puerto Rico Department of Natural and Environmental Resources (DNER) is responsible for the administration of Puerto Rico's coastal public trust lands, the maritime terrestrial zone, territorial waters and submerged lands thereunder [PR Law 23, Art.5(h)]. DNER also serves as the lead agency for the implementation of the Puerto Rico Coastal Zone Management Program (PRCZMP) which was adopted in 1978 as the coastal element of the Island-wide Land Use Plan. The PRCZMP is a partnership between the United States federal government through the National Oceanic and Atmospheric Administration (NOAA) and the Government of Puerto Rico (DNER and PR Planning Board) authorized by the Coastal Zone Management Act (CZMA) of 1972 to address national coastal issues.[1] The Act provides the basis for protecting, restoring, and responsibly developing the United States' diverse coastal communities and resources. To meet the goals of the CZMA, the National CZM Program takes a comprehensive approach to coastal resource management— balancing the often competing and occasionally conflicting demands of coastal resource use, economic development, and conservation.

Principles of the PRCZMP:

- Develop guidance for public and private development within the coastal zone.
- Active management of coastal and marine resources.
- Promoting scientific research, education and public participation.
- Coordinating state and federal actions.

The primary responsibility of the PRCZMP is to guide public and private development within the coastal zone (Figure 1). As part of its ministerial duty PRCZMP has analyzed coastal dynamics trends and conducted Island-wide or site-specific historical shoreline change studies based on sequential aerial photography (1930-2017) and LIDAR images comparison (2004-2018). The analyses have revealed multiple active erosion segments of the coasts of Puerto Rico, Culebra and Vieques. Additional analyses of the geological and geomorphic processes that serve as basis to conduct trends analysis and assessments of coastal changes were conducted by Kaye and Clifford (1959) and Morelock (1978).

In 1995, Dr. Dave Bush in collaboration with José González-Liboy, Lysbeth Hyman, and Richard Webb published the book *Living with the Puerto Rico Shore* (Bush et al, 1995) where the authors assess coastal dynamic trends along all Puerto Rico's coastal segments. In 2015, the PRCZMP retained the professional services of the University of

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[1] For more information on the Coastal Zone Management Program, see the NOAA website at https://coast.noaa.gov/czm/act/.

Puerto Rico - Rio Piedras to conduct the assessment of beach erosion trends in Puerto Rico. This study was led by Dr. Maritza Barreto who served as principal investigator. The report titled *Assessment of Beach Morphology at Puerto Rico Island* was submitted to DNER-PRCZMP and published in 2017 (Barreto 2017). Dr. Barreto's study shows that between 1977 and 2010, 60% of the area that meet the geomorphological definition of beaches, face moderate to severe erosion.

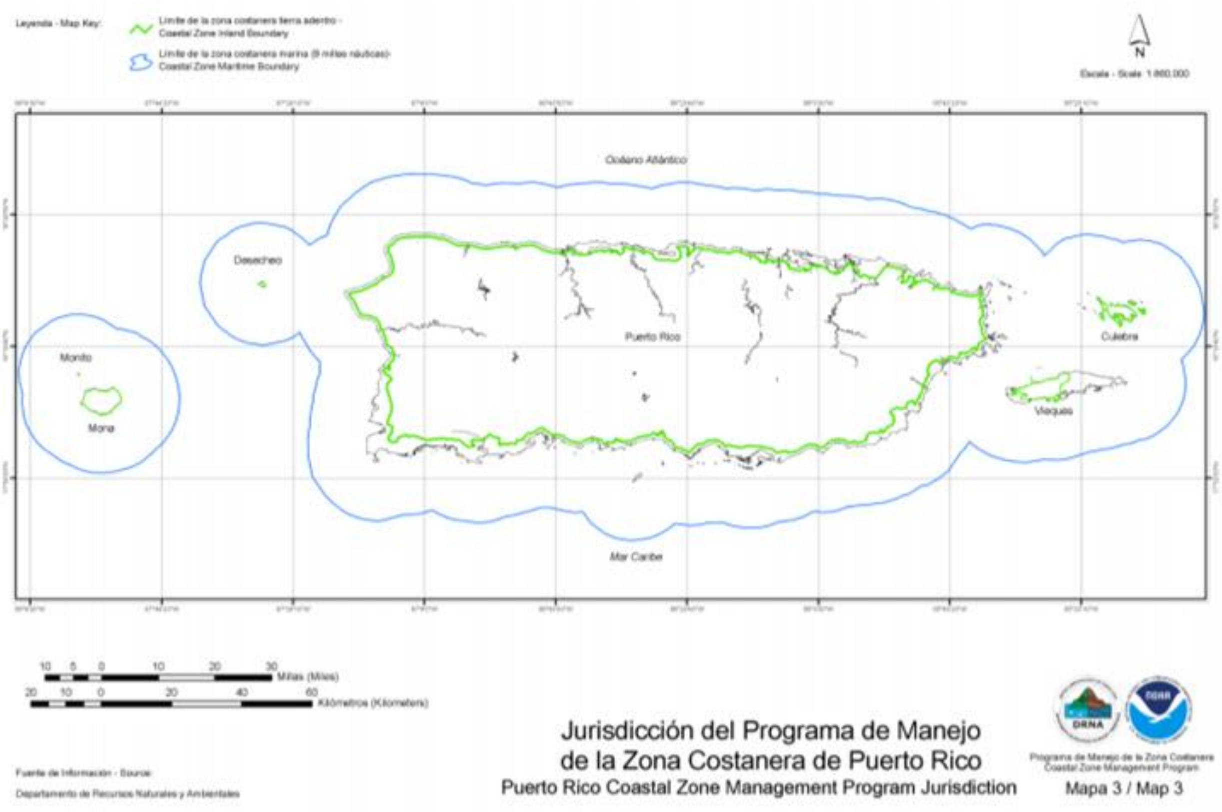

Figure 1. Puerto Rico Coastal Zone Management Program Jurisdiction.

In addition, the PRCZMP has funded and collaborated in the development of the storm surge atlas for hurricanes categories 1 through 5, as well as 0.5- and 1-meter sea level rise inundation scenarios[2].

Puerto Rico faces multiple coastal management challenges, including increasing development pressures, land-based sources of pollution, wetlands and coral reef degradation, dune systems alteration, beach erosion and coastal hazards, among others. These threats have been exacerbated during the last decade as Puerto Rico faces more frequent and intense extreme storm events. The 2017 Atlantic hurricane season has been the most active in modern history. During 2017, Puerto Rico's coastal communities, critical infrastructure as well as coastal and marine habitats were severely impacted by the devastating power of hurricanes Irma (September 6, 2017) and hurricane Maria

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[2] The storm surge atlas is available at www.pr-ccc.org .

(September 20, 2017). Coastal erosion was exacerbated not only by cumulative wave action associated with hurricanes Irma and Maria but also to the 5-day high energy wave action from Winter Storm Riley in March 2018. Doctors Luis Aponte, Miguel Canals, Francisco Villafañe and Ernesto Díaz published a paper at the Professional Engineers Association discussing the impacts of coastal erosion on Rincon's infrastructure (CIAPR Dimensión, Año 31, Vol. 1, 2017). After the impacts of hurricane María, staff from DNER-PRCZMP conducted damage assessments at 370 sites in 43 of the 44 coastal municipalities. Also, Dr. Luis Aponte, Dr. Miguel Canals, Dr. Jonathan Muñoz, Dr. Patricia Chardon and Ernesto Díaz conducted post-hurricane damage assessments at Rincón, Ocean Park, Santa Isabel, and Barceloneta. Cumulative impacts of high energy wave action resulting from hurricanes Irma, María, and Winter Storm Riley, as part of the 2017 Atlantic Hurricane Season and the Winter Swells season 2018 exacerbated the already battered beaches of the North, Northeast, Northwest, and West coasts of Puerto Rico, as well as beaches of Culebra and Vieques, causing major public and private infrastructure loses. Multi-unit residential buildings and small hotels at Rincón collapsed due to storm wave action, and extensive debris remains 18 months after Maria along the upper reach of the beach affecting beach aesthetics and tourism. As an example, coastal communities' vulnerabilities (summer homes and lower income dwellings) increased due to unexpected 2018 major erosion events. Natural infrastructure such as coral reefs, dunes, and coastal wetlands also suffered severe mechanical and abrasion damages during 2017 and 2018 hurricanes and Winter storms, therefore reducing their structural complexity, ecosystem services and coastal protection capacity. These social-ecological vulnerabilities, trends and projections are examined as part of the US Caribbean chapter of the Fourth National Climate Assessment report.[3] .

Engineering projects occurring within specific segments of the Puerto Rico shores must take into account the specific context, trends, before-after conditions, beach or coastal segment position, presence of coral reefs, eolianites, prevailing winds and wave direction, wave energy and design criteria (wave climate), among others. The need for engineering interventions may be the result of: (1) an emergency, (2) need of a concession or (3) regional sediment management project. These interventions will need a permit or concession issued by DNER under Regulation 4860 (1992, as amended).[4]

To develop resilience in the face of climatic challenges and sea level changes, DNER recognizes that it is critically important to use the best available science to guide decision-making processes in Puerto Rico around coastal development and natural resource management. For the purposes of this document, the following definition applies:

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[3] Find the Fourth National Climate Assessment report online at https://nca2018.globalchange.gov/chapter/20/.

[4] Find a description of Regulation 4860 and application forms online at http://drna.pr.gov/tag/reglamento-4860/.

Resilience: The ability to avoid, minimize, withstand, and recover from the effects of adversity, whether natural or man-made, under all circumstances of use. This definition also applies to engineering, ecological, and community resilience.

DNER launched the project, Strengthen Coastal Resiliency in Puerto Rico, in February 2017 to help strengthen local and provisional coastal resiliency efforts based on best available science and practices. Two activities have been developed to support the project goal:

1. Development of this **Coastal Engineering Handbook** that identifies best practices in addressing coastal erosion and that can be used as a tool for Commonwealth and local governments to evaluate and make permitting decisions, as well as for planners, scientists and engineers interested in best practices.
2. Development of a companion **Coastal Resiliency Funding Guide** (DNER and Tetra Tech, 2018) that provides recommendations for local governments and communities to think more comprehensively about resiliency and find ways to increase the feasibility of implementing solutions through identification of potential funding strategies, such as public private partnerships, federal grants and resources, and other local funding mechanisms.

It should be noted that the tasks have been designed as synergistic—each component is able to leverage the findings and stakeholder networks of the others to streamline results across tasks and create greater impact for available resources.

1.2. Coastal Engineering Handbook

As an island archipelago in the Caribbean, Puerto Rico is particularly sensitive to natural hazards such as hurricanes, extreme precipitation events, and coastal storm surges. The coastline of the archipelago has a length of 700 miles[5], of which, 484 miles are on the main island. Approximately 419,000 people live within Puerto Rico's coastal zone, which is defined as 1 kilometer from the coastline (Diaz and Hevia, 2011). However, all of Puerto Rico is classified as a coastal area, and includes appropriately 3.5 million people. Sixty one percent (61%) of the population live within its 44 coastal municipalities. Puerto Rico's entire population is exposed to some degree of risk from coastal hazards. There are also significant critical or essential infrastructure/facilities that are located in the coastal zone (Diaz, 2014), including:

- 12 ports
- 13 airports
- 7 power generation facilities (5 public and 2 private)
- 1,080 miles of sanitary infrastructure
- 28 wastewater treatment plants
- 81 industrial parks

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[5] https://coast.noaa.gov/states/puerto-rico.html.

There is a 24% built-up to coastline ratio. Many residential, industrial and commercial buildings, as well as port, marinas, coastal protection infrastructure, roads, bridges, culverts, bike and pedestrian routes, and cultural and historic sites, among others are also at risk. The exposure of relatively high population levels and the amount of infrastructure in the coastal zone underscores the amount of historic development that has occurred in the island's high hazard areas. Puerto Rico's homeowners, businesses, and municipalities located along the coast have often employed hard infrastructure shore protection options, such as vertical seawalls and gabions to combat coastal erosion. However, if they are not designed properly, these infrastructure options generally relocate the problem downdrift or to another part of the coast. In fact, the application of gabions as a coastal shore protection measure has been a common practice in PR for decades, and has proven time and time again its ineffectiveness due to corrosion of the wire mesh and the under sizing of the rock for any given high energy coastal environment. Other conventional coastal protection structures such as rubble mound breakwaters, jetties, and groins can be found along PR's shoreline. DNER has also noted that many of the existing shoreline stabilization structures are poorly maintained (PRCCC, 2015).

Puerto Rico also has significant environmental and natural resources (coral reefs, beaches, and mangroves) that are sensitive to coastal hazards, as well as historically affected by a variety of land-based stressors. Coastal development has resulted in the conversion of some of these features. Poor soil and sediment management practices and poor maintenance of stormwater management systems have resulted in sedimentation and water quality issues that negatively impact environmental and natural resources (PRCCC, 2015). The health and distribution of Puerto Rico's natural resources are important not just from a biodiversity and habitat standpoint, but because they also serve as naturally protective features from coastal hazards. Coral reefs provide effective coastal protection from waves. The high structural complexity of coral reefs results in high hydraulic roughness and greater frictional dissipation of waves when compared to other coastal settings (Harris et al, 2018)

Climate change is expected to exacerbate the threat of natural hazards and vulnerability of Puerto Rico's people, infrastructure, and environmental and natural resources. As a result of climate change, average temperatures and sea levels are rising, precipitation patterns are changing, and hurricanes could intensify.

DNER has long recognized the vulnerability of Puerto Rico and its surrounding islands to coastal hazards and climate change and has championed proactive measures to address these multi-faceted issues. DNER has supported efforts to quantify and characterize Puerto Rico's shoreline, and has developed free, publicly-available visualization tools which can be used for planning purposes to assess the vulnerability of coastal areas under various sea level rise scenarios and hurricane intensities.[6] The University of Puerto Rico at Mayaguez houses two programs that provide the best wave data, modeling, simulations and forecast to support decision making in Puerto Rico: the Caribbean

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[6] Visualization tools can be found at http://planner.caribbean-mp.org and pr-ccc.org

Coastal and Ocean Observing System (CARICOOS) and the Center for Applied Ocean Science and Engineering (CAOSE).[7]

Building on the findings of these efforts, this coastal engineering handbook is intended to identify locally applicable best practices in an easy-to-use format. One of the primary goals for this manual is to present approaches and recommendations that move away from the practice of protecting one property, one section of a failed road or one structure, and toward the consideration of collective or regional opportunities for coastal protection. Additionally, this handbook presents case studies, recommendations and guidance to move away from implementing hard infrastructure options that may have downdrift impacts, to consider nature-based solutions that provide increased protection from coastal hazards and also provide multiple co-benefits, whenever possible. To do this, much of the existing coastal protection systems will need to be removed and replaced or at least modified to mitigate potential adverse effects and increase their resiliency to further damage.

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[7] Examples of the data and modeling capabilities of these organizations can be found at: https://www.caricoos.org/waves/forecast/SWAN/PRVI/hsig

2 STATE OF SHORELINE PROTECTION IN PUERTO RICO

2.1 Traditional Practice

The shores of Puerto Rico are especially vulnerable to coastal hazards both now and increasingly so in the future. These hazards include waves and surge flooding associated with coastal storms. Sea level changes will exacerbate the potential damage threats from these coastal hazards in the future.

The traditional response to coastal hazards across the world, including Puerto Rico, has been to design and implement vertical coastal structures to protect individual properties. The approach is short-sighted since it fails to recognize some of the effects of vertical structures on both the project site as well as on adjacent coastal areas. For example, a seawall structure resists wave forces by reflecting all or most of the energy seaward. Vertical seawalls can act as almost perfect reflectors, while other hardened structures such as revetments dissipate some wave energy and reflect a reduced amount of wave energy back out to sea.

The problem with the highly reflective condition is that incoming waves combine with the reflected waves and significantly increase the local wave heights and their associated energy. In the case of a perfectly reflecting vertical seawall, the local wave heights at the face of the wall can almost double the size of the incoming sea waves. This localized increased wave energy environment can quickly erode any sandy beach that may exist seaward of the seawall. Depending on the composition of the foundation materials beneath the seawall, the seawall may eventually be undermined by erosion and fail. Perhaps more importantly, vertical seawalls can also exacerbate beach loss due to the excessive sediment suspension caused by increased wave action.

The second challenge with hardened coastal structures such as groins or shore perpendicular structures is that they may affect sediment transport along adjacent shorelines if they are not properly designed. By reducing the sediments that would normally feed the downdrift beaches, hardened and vertical coastal structures often result in accelerated erosion of those sediment-starved areas. This can contribute to more rapid shoreline recession rates as well as exposure or flanking at the ends of the coastal structures, leading to their possible localized failure. This is the main reason why coastal structures need rigorous analysis and design on a regional or coastal segment basis such as an embayment or a littoral cell.

2.2 Current Coastal Engineering Practices

Current coastal engineering practice throughout the US looks beyond the individual property limits and considers regional conditions. It also considers the full spectrum of coastal stabilization techniques that may be applied either alone or in concert with additional techniques.

An example of this broader practice is the US Army Corps of Engineers (USACE) coastal planning approach (USACE, 2013). The USACE planning approach supports an integrated strategy for reducing coastal risks and increasing human and ecosystem community resilience through a combination of the full array of measures: natural, nature-based, nonstructural, and structural. This approach considers the engineering attributes of the component features and the dependencies and interactions among these features over both the short and long term. It also considers the full range of environmental and social benefits produced by the component features.

The USACE (ERDC/EL SR-18-8) developed the Engineering with Nature Atlas[8]. The Atlas is described as a collection of projects that illustrate a diverse portfolio of contexts, motivations, and successful outcomes. The projects were developed collaboratively to integrate natural processes into engineering strategies that support navigation, flood risk management, ecosystem restoration, or other purposes. Developing projects that combine natural and engineered systems to produce more value and a broader array of benefits is gaining increasing attention worldwide.

The USACE and NOAA have also engaged partners and stakeholders in a community of practice called Systems Approach to Geomorphic Engineering (SAGE)[9]. This community of practice provides a forum to discuss science and policy that can support and advance a systems approach to implementing risk reduction measures that both sustains a healthy environment and creates a resilient shoreline. SAGE promotes a hybrid engineering approach that integrates soft or 'green' natural and nature-based measures, with hard or 'gray' structural ones at the landscape scale. These stabilization solutions include "living shoreline" approaches which integrate living components, such as plantings, with structural techniques, such as seawalls or breakwaters.

A SAGE brochure is included in this report as Annex A. The brochure provides the full spectrum of coastal stabilization techniques with illustrations, recommendations for usage, material requirements, advantages and disadvantages. The brochure as well as the SAGE website include links to engineering and scientific guides, policy papers, webinars, example projects, activities announcements and contact information for SAGE staff.

Given the lack of a programmatic approach to shoreline management and protection in Puerto Rico, as well as poorly designed or maintained coastal features, the typical reaction is to repair a failed structure and replace it with something similar. This current local practice should stop and regulators and engineers should have the basic knowledge and tools to recognize when a replacement in kind should not be implemented.

The most common coastal structural failures observed along urban beaches in Puerto Rico are gabions and vertical seawalls. Failed gabions must be removed, and before replacing it with a revetment or another type of seawall with scour protection along its toe, an appropriate analysis must be conducted. The basic concept is to identify the cause,

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[8] Bridges, T. S., E. M. Bourne, J. K. King, H. K. Kuzmitski, E. B. Moynihan, and B. C. Suedel. 2018. Engineering With Nature: an atlas. ERDC/EL SR-18-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/27929.

[9] Systems Approach to Geomorphic Engineering, Resilient Coasts, SAGE, Thriving Communities URL: http://www.sagecoast.org/

mechanism, and type of erosion. Causes of erosion may include extreme storm events, long shore currents, and/or lack of sediment sources. Mechanisms of erosion may include direct wave impact, long and short period waves and directions, sustained winds, etc. Types of erosion may be progression erosion, seasonal erosion, or periodic-storm driven erosion. Once these parameters are understood, the erosive forces may be managed by dissipation offshore or nearshore, if possible, coupled with beach nourishment, or some combination of both which may create additional habitats and ecological restoration opportunities (e.g., artificial reefs, living shorelines, vegetated sand dunes, etc.) This approach is further discussed in detail in Section 5.2 of this guideline.

Beach nourishment projects typically implemented by the USACE in coastal states in the US have never been applied in Puerto Rico. The coastal or lagoon restoration projects which have been developed and implemented in the past decades have been primarily funded by US federal grants from NOAA, USFW, and NRCS, or by funds resulting from legal settlements of groundings and oil spills or man-caused disasters.

The DNER, through the Coastal Zone Management Program, has finally in 2017 received the support of the USACE Jacksonville District to conduct two feasibility studies under Section 204 of the Rivers and Harbors Act of 1970 (Public Law 91-611). These studies are the first coastal studies funded under the USACE authorities for Puerto Rico. The primary National Economic Development (NED) benefit focuses on Storm Damage Reduction Benefits. Incidental NED Benefits include the reduction of damages and protection of critical infrastructure as well as the projection of existing tourism related facilities and assets.

2.3 Sources of Coastal Risks

The coast of Puerto Rico is facing increased risk due to the effects of an array of stressors. These include:

- Coral reef deterioration due to coral bleaching
- Increased beach erosion due to more severe and more frequent storms
- Sea level rise
- Improperly sited or located coastal development
- Inadequately selected and/or designed coastal protection measures

Coral Reef Deterioration - Healthy coral reefs provide a significant contribution to coastal stability because they can dissipate normal and storm waves before they impact on the shore. Coral reef bleaching is impacting reef systems worldwide. Increased sea temperatures and waste/stormwater discharges can stress corals which leads to the expelling of the symbiotic algae that live in them, turning the coral white. In addition, ocean waters are undergoing acidification due to the absorption of CO2 from the atmosphere. Recent studies show that ocean acidification is a two-front assault on coral reefs, simultaneously slowing the growth of skeleton, and speeding up the rate at which old reef habitats are bio-eroded by worms and other organisms (Enochs et al., 2017).

A healthy, resilient reef can either resist a stressful event, like bleaching, or recover from it. When a coral bleaches, it may recover if the heat stress period is not prolonged. Corals can survive if water temperatures and/or water quality return to normal quickly. If the stress is maintained, the coral can die and be subject to deterioration under the action of waves and currents. Loss of the coral reef will increase the wave energy that impacts the shore. Over the last century, humans have driven global climate change through industrialization and the release of increasing amounts of CO2, resulting in shifts in ocean temperature, ocean chemistry, and sea level, as well as increasing frequency of storms, all of which can profoundly impact marine ecosystems. Coral reefs have suffered massive declines in health and abundance as a result of these and other direct anthropogenic disturbances. There is great concern that the high rates, magnitudes, and complexity of environmental change are overwhelming the intrinsic capacity of corals to adapt and survive. It is imperative to determine the feasibility of developing coral stocks with enhanced stress tolerance through the acceleration of naturally occurring processes, an approach known as (human)-assisted evolution, while at the same time initiating a public dialogue on the risks and benefits of this approach[10].

Robust scientific literature provides evidence that a healthy reef can attenuate over 90% of incoming wave energy (Harris, et. al., 2018). Furthermore, the reef crest attenuates the majority of the wave energy. For that reason, the PRDNER has requested Public Assistance funding under Section 428 of the Stafford Act (FEMA, 2018) to restore coral reefs as critical maintained natural infrastructure.

More Frequent Storms - Climate change may result in more frequent and more intense storms. It is unknown how the total number of tropical cyclones will change in the North Atlantic Basin. However, it is likely that the number of the more intense hurricanes will increase in the North Atlantic Basin, along with the extreme winds associated with those strong storms. Even if the strongest hurricanes become more frequent in the North Atlantic Basin, the implications for Puerto Rico are unclear because individual storm tracks are highly variable and potential changes in tropical cyclone tracks are poorly understood.

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[10] Van Oppen, Madeleine & Oliver, James & Putnam, Hollie and Gates, Ruth. (2015). Building coral reef resilience through assisted evolution. Proceedings of the National Academy of Sciences. 112. 10.1073/pnas.1422301112.

Sea Level Rise – Global Mean Sea Level (GMSL) has increased by about 21 centimeters (cm) since 1880. Figure 2-1 shows the long term mean sea level trend for the tide gage station at San Juan. Sea level is rising in Puerto Rico at the rate of 2.08 mm/yr. Recent projections consider the potential for rapid ice melt in Greenland and Antarctica (NOAA, 2017). The projections support a physically plausible GMSL rise in the range of 2.0 meters (m) to 2.7 m over the next 100 years. Recent results regarding Antarctic ice-sheet instability indicates that such outcomes may be more likely than previously thought. NOAA now recommends a revised ‘extreme’ upper-bound scenario for GMSL rise of 2.5 m by the year 2100, which is 0.5 m higher than the previous upper bound scenario.

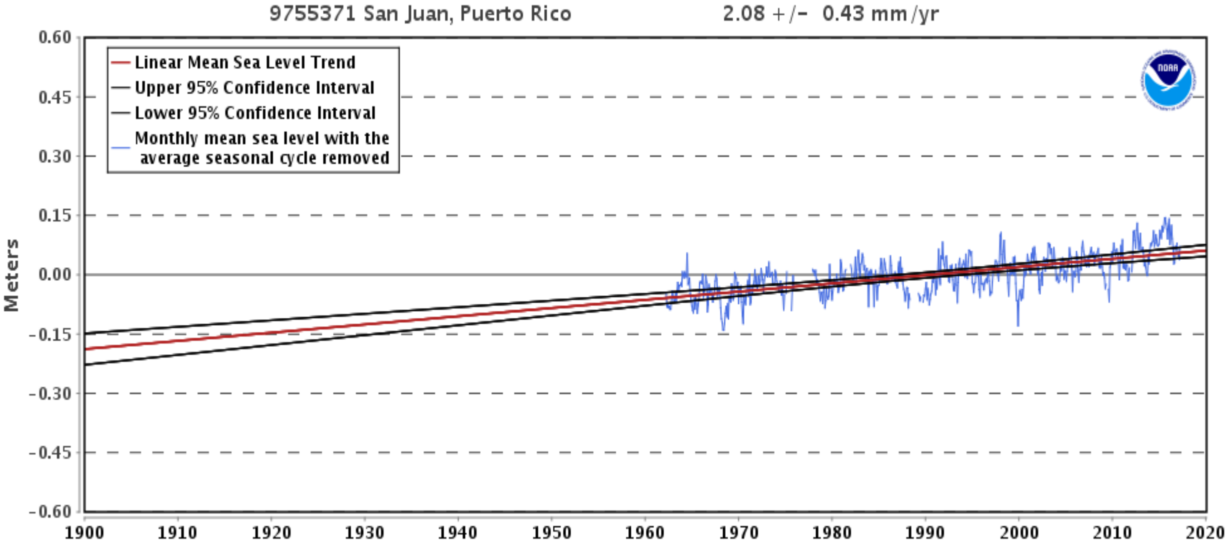

Figure 2. Long-term sea level trend for the ride gage station at San Juan.

NOAA (2017) provides the following comprehensive summary of the effects of sea level rise on US coasts:

“While the long-term, upward shift in sea level is an underlying driver of changes to the nation’s coasts, impacts are generally expressed through extreme water levels (short-period, lower-probability events both chronic and acute in nature) occurring against the background of this shifting baseline. Higher sea levels worsen the impacts of storm surge, high tides, and wave action…, even absent any changes in storm frequency and intensity. Even the relatively small increases in sea level over the last several decades have led to greater storm impacts at many places along the U.S. coast … Similarly, the frequency of intermittent flooding associated with unusually high tides has increased rapidly (accelerating in many locations) in response to increases in relative sea level (RSL) ….

At some locations in the United States, the frequency of tidal flooding (events typically without a local storm present) has increased by an order of magnitude over the past several decades, turning it from a rare event into a recurrent and disruptive problem… Significant, direct impacts of long-term RSL rise, including loss of life, damage to infrastructure and the built environment, permanent loss of land…, ecological regime shifts in coastal wetlands and estuary systems …, and water quality impairment …, also occur when key thresholds in the coastal environment are crossed … Some of these impacts have the potential to ‘feedback’ and influence wave impacts and coastal flooding. For example, there is evidence that wave action and flooding of beaches and marshes can induce changes in coastal geomorphology, such as sediment build up, that may iteratively modify the future flood risk profile of communities and ecosystems …"

Coastal Development at Risk. The coastal zone is an unforgiving environment. Development decisions that ignore the natural processes influencing the coastal system are inevitably subject to failure. Compounding the problem is the fact that such careless development will not be just limited to the footprint of that development; it will affect adjacent areas for significant distances along the coast. Therefore, unplanned coastal development must be viewed as a regional and not as a localized, site specific problem.

This is a chronic and typical problem in Puerto Rico, recently evidenced by the numerous dwellings and structures that were not planned, designed and constructed, or protected which have catastrophically failed, resulting in further damage and deterioration of our coastlines. Many such examples can be found along the shorelines of the municipalities of Rincon, Aguadilla, Isabela, Arecibo, Barceloneta, Vega Baja, Dorado, San Juan, Loiza, Rio Grande, Humacao, Yabucoa, Arroyo, to name a few.

Properly planned coastal development will provide resiliency, functional performance, and stability. There are tools available for planners and engineers to properly develop coastal properties which include setbacks, elevation adjustments, and protection which support resilient coastal development. However, it is up to the property owner and the governmental entity with jurisdiction to plan and enforce appropriate developments.

Figure 3. Failure of unprotected vertical structures in Rincon after Hurricane Maria.

Inadequate Coastal Protection Measures. Often times, property owners, engineers and even public corporations react to a severely eroded condition by implementing unplanned or improperly designed remedial solutions such as gabion walls, undersized revetments, or unanchored foundations. These existing inadequate measures must be remediated and corrected with proper engineering analysis, criteria and design tools, some of which are presented within this handbook.

2.4 Beach Types and Settings in PR

The Puerto Rico Department of Natural and Environmental Resources commissioned a study in 2016 (Barreto, 2017) which produced a classification and an inventory of the various types of shorelines throughout Puerto Rico. The shorelines were characterized in four primary types: sandy beaches, rocky shorelines, mangroves or vegetated shorelines, and alluvial plains. Secondary categories include: man-made structures, such as marinas, breakwaters, houses; and naturally occurring sedimentary rock structures.

Sandy beaches are the predominant type of shoreline and most frequently occur along the principal urban and residential areas. Sandy beaches are also the most vulnerable and erosive type of shoreline. In many instances, given the lack of sound coastal development planning processes, vertical seawalls and bulkheads are constructed to serve as the first line of coastal defense. The beach in front of these vertical structures may fluctuate and erode seasonally, as observed in several urban beaches such as Luquillo, Ocean Park and Rincon. However, once the eroded profile exposes the vertical structure, wave action is no longer dissipated, and instead it is magnified by the reflective nature of the vertical seawalls causing an accelerated erosion effect, which sometimes results in the permanent loss of sand.

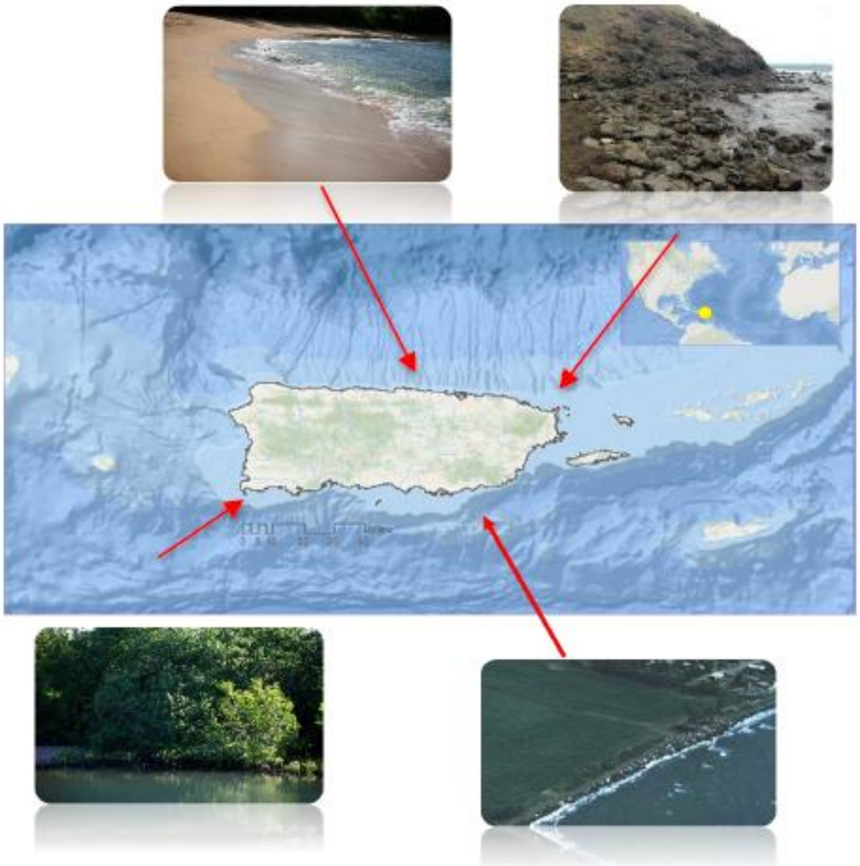

Figure 4. Shoreline types (sandy, rocky, mangroves or vegetated, and alluvial plain) from Barreto (2017).

One of the objectives of this handbook is to establish guidelines and parameters to address these cases, and mitigate risks associated to the permanent loss of beach sand.

2.5 Critical and Vulnerable Areas In Puerto Rico

Shorelines are highly dynamic systems that naturally interact with terrestrial, marine and atmospheric processes and experience continuous change in response to these processes. Over the years, human society has, to a great extent, failed to recognize this dynamic character of coastal areas, and this has led to major disasters and societal disruption of various degrees. Even today, coastal development is often taking place with little regard to natural dynamics, and this problem is especially pronounced in developing countries where data, technical expertise and economic resources are limited and coastal populations are growing rapidly. The predicted climate change adds an extra risk factor to human activities in coastal areas. While the natural dynamics that shape our coasts have been relatively stable and predictable over the last centuries, rapid change is now expected in processes such as sea level rise, ocean temperature, ocean acidity, tropical storm intensity and precipitation/runoff patterns (IPCC, 2013)[11] . The world's coastlines will respond to these changes in different ways and at a different pace depending on their bio-geophysical characteristics, but generally society will have to recognize that past coastal trends cannot be directly projected into the future. Instead, it is necessary to consider how different coastal environments will respond to the predicted climate change and identify relevant management options. Furthermore, improved coastal communication is essential for development of management strategies within the broader framework of Integrated Coastal Zone Management (ICZM) (Appelguist et al., 2016).

This report examines critical and vulnerable coastal areas of Puerto Rico using the Coastal Hazard Wheel (CHW) decision support system as the analysis tool, together with inputs from the Puerto Rico DNER Coastal Inventory GIS database and associated references. Figure 5 illustrates the CHW. The CHW uses a coastal classification system that distinguishes between 131 generic coastal environments. The analysis includes consideration of the wave exposure at the site, the tidal range, flora/fauna characteristics, estimation of the sediment balance, and the determination of the storm climate. The CHW analysis then yields hazard evaluations with respect to five hazards that include: 1) ecosystem disruption; 2) gradual inundation; 3) salt water intrusion; 4) erosion; and 5) flooding. In total, 655 individual hazard evaluations are possible, and these are divided into four different hazard levels describing the relative hazard level for each particular coastal type.

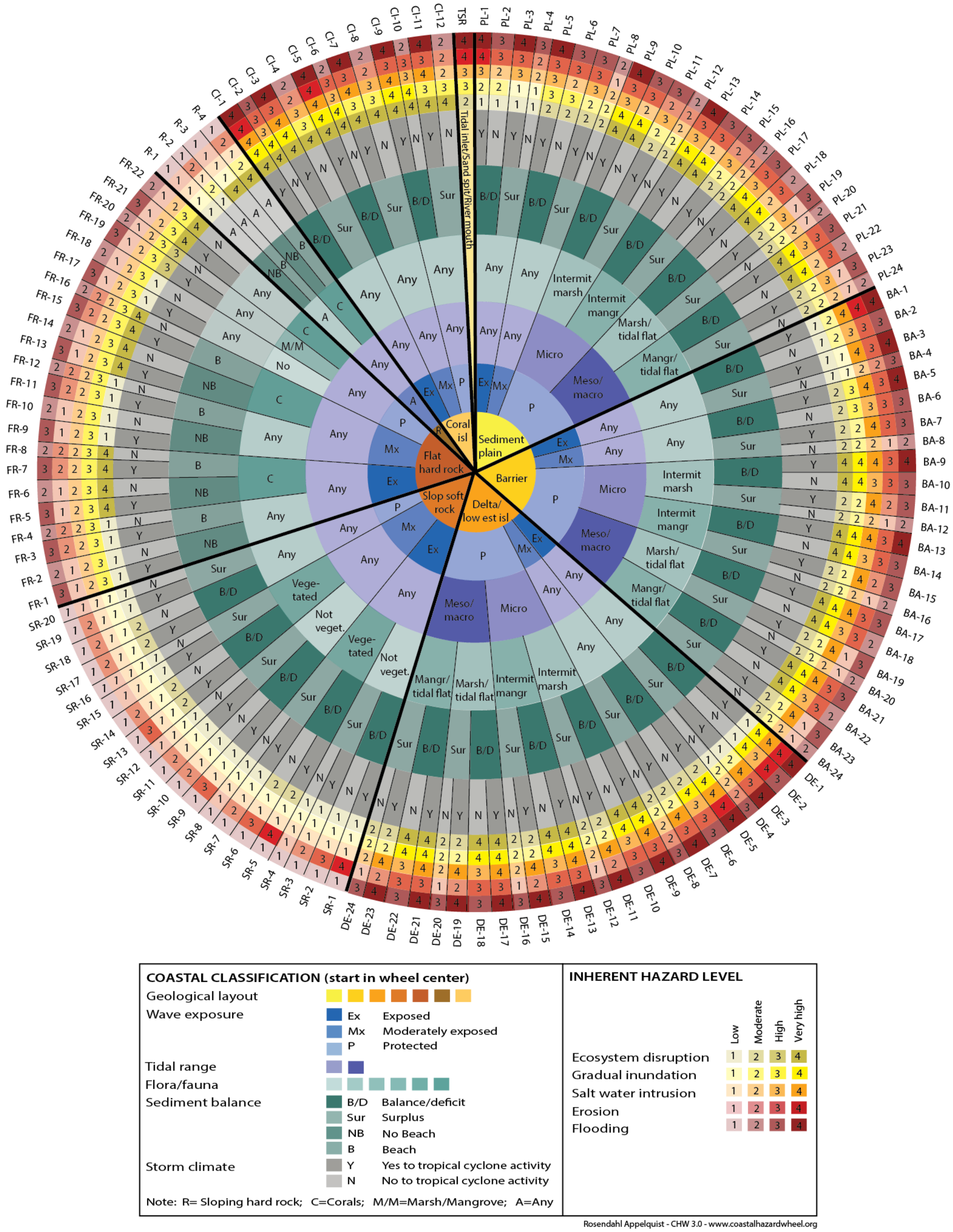

Figure 5. Coastal Hazard Wheel Decision Support System (Appelguist et al., 2016).

3 JURISDICTIONAL AND REGULATORY CONTEXT

Every project along the coastline, whether improvements to an existing structure, new project, or emergency updates during a federally declared disaster must go through a regulatory screening/analysis to determine which laws, rules and regulations apply to the project. A summary of the local and federal jurisdictional requirements for a coastal engineering project is shown in Figure 6 (i.e. Flowchart #1).

All projects, whether they are an emergency project that must occur in the timeframe a federally declared disaster, or existing or new improvements, must also comply with Article 4(B)(3) of the Puerto Rico Environmental Public Policy Act No. 416 of 2004. The regulatory and permitting process for compliance with Article 4(B)(3) is shown in Figure 7 (i.e. Flowchart #2).

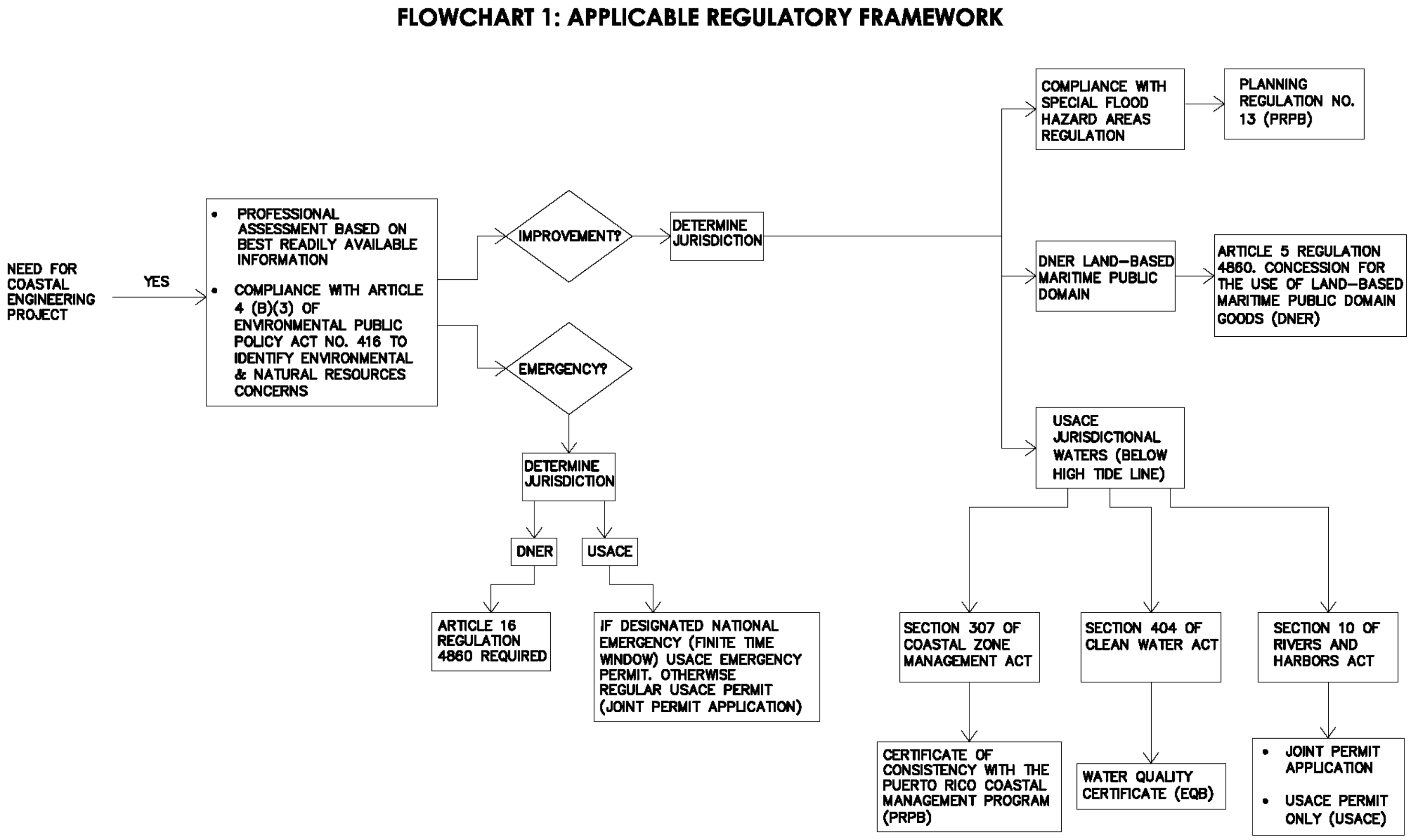

Figure 6. Flowchart #1: Local and Federal regulatory framework for coastal engineering projects in Puerto Rico.

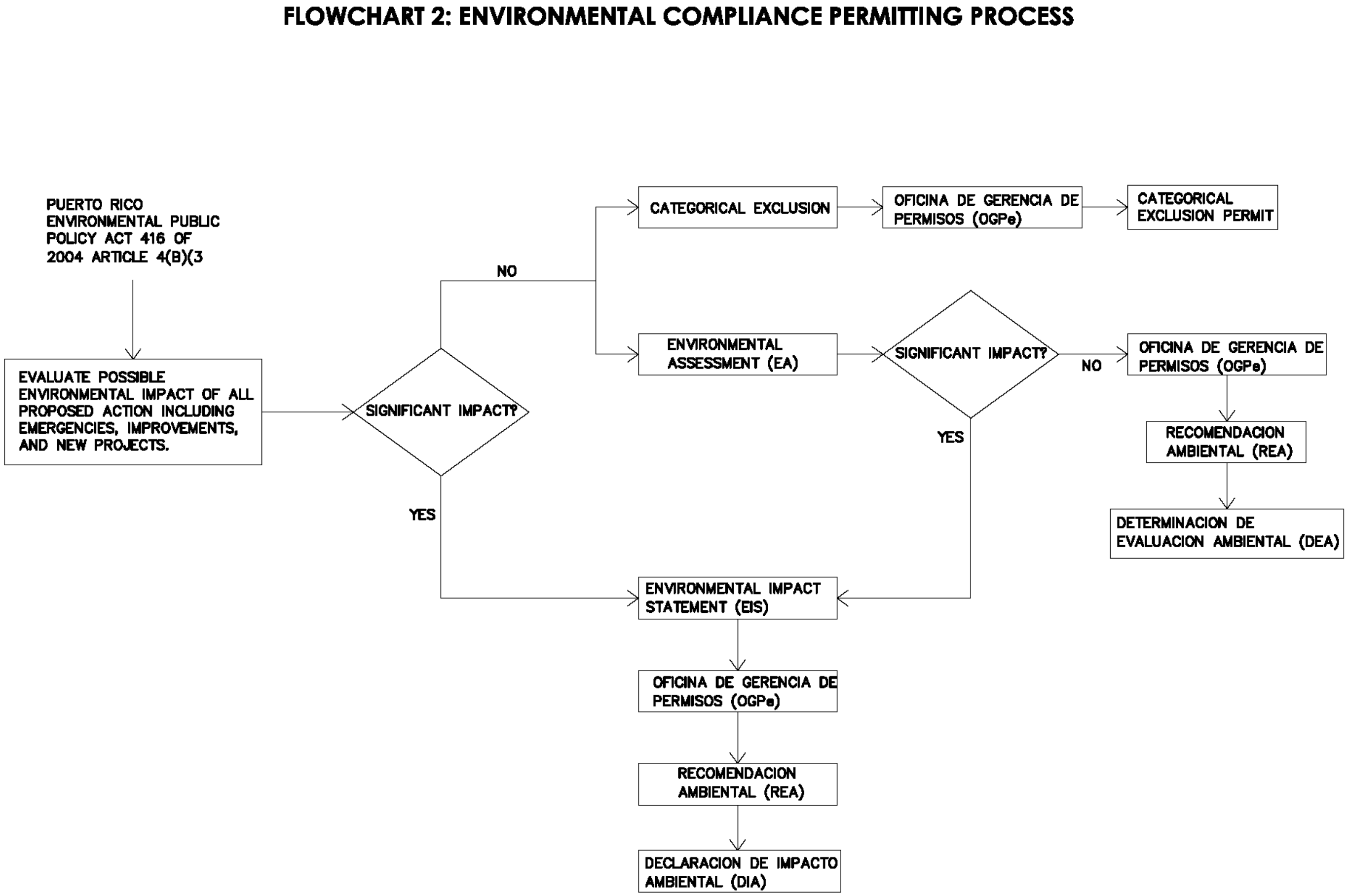

Figure 7. Flowchart #2: Typical process for compliance with Article 4(B)(3) of the Puerto Rico Environmental Public Policy Act No. 416 of 2004.

3.1 Compliance with Article 4(B)(3) of Act No. 416

Article 4(B)(3) of the Puerto Rico Environmental Public Policy Act No. 416 of 2004 is also known as "Puerto Rico Water Quality Standards Regulation". The regulation is derived from the National Environmental Policy Act (NEPA) of 1969 and its counterpart in NEPA, Section 102(2)(C). The purpose of the PR Water Quality Standard Regulation is to evaluate possible environmental impacts of all proposed actions within jurisdictional waters of both the United States and territorial waters of Puerto Rico, including emergency actions, improvements, and new projects. The process begins when a proposal to take a major federal action is developed. The environmental review involves three different possible analyses; Categorical Exclusion (CATEX) determination, Environmental Assessment (EA), or Environmental Impact Statements (EIS).

An action can be categorically excluded from detailed environmental analysis if it does not have significant impacts on the human environment.[12] If a CATEX does not apply to the proposed action, an EA is prepared to determine if the proposed action has the potential to cause significant environmental impacts. The determination of no significant impact for the EA analysis is a two-step process carried out through the Permits Management Office (OGPe, by its acronym in Spanish) starting with an Environmental Recommendation (REA, by its acronym in Spanish) and ending with a Determination of Environmental Compliance for Environmental Assessment (DEA, by its acronym in Spanish). If the proposed action is determined to have significant environmental impacts and potential to affect the quality of the human environment, an EIS document is required.

The above-mentioned environmental documents (EA and EIS) are reviewed by the OGPe and all pertinent local and federal regulatory and resource agencies. The DEA issued by OGPe is the evidence of environmental compliance.

3.2 Federal Regulatory Requirements (USACE)

The U.S. Army Corps of Engineers' (USACE) Regulatory Program regulates discharges of dredged or fill material into waters of the United States as well as the placement of structures or performance of other work in navigable waters of the United States. USACE will issue permits pursuant section 404 of the Clean Water Act for discharges of dredged or fill material into waters of the United States and pursuant to Section 10 of the Rivers and Harbors Act of 1899 for placement of structures or performance of other work in navigable waters of the United States. Frequently, the provisions of both laws will apply to an individual proposed action.

The scope and extent of the potential impacts of a proposed project will determine what permit type is required. An individual, or standard permit, is issued when projects have more than minimal individual or cumulative impacts, are evaluated using additional environmental criteria, and involve a more comprehensive public interest review. A general permit may be issued for structures, work or discharges that will result in only

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[12] List of Categorical Exclusions (in Spanish) can be found online at: https://www.ddec.pr.gov/wp-content/uploads/2019/03/R-11-17_Resolucion_sobre_Exclusiones_Categoricas.pdf

minimal adverse effects. General permits are issued on a nationwide, regional, or state basis for particular categories of activities.

There are three types of general permits – Nationwide Permits, Regional General Permits, and Programmatic General Permits. General permits are usually valid for five years and may be re-authorized by the USACE.

- Nationwide permits are issued by USACE on a national basis and are designed to streamline Department of the Army authorization of projects such as commercial developments, utility lines, or road improvements that produce minimal impact the nation's aquatic environment.
- A regional general permit is issued for a specific geographic area by an individual USACE District. Each regional general permit has specific terms and conditions, all of which must be met for project-specific actions to be verified. Programmatic general permits are based on an existing state, local, or other federal program and designed to avoid duplication of that program.
- A State Programmatic General Permit (SPGP) is a type of permit that is issued by USACE and designed to eliminate duplication of effort between USACE districts and state regulatory programs that provide similar protection to aquatic resources. In some states, the SPGP replaces some or all of the USACE nationwide permits, which results in greater efficiency in the overall permitting process.

Potential applicants for USACE permits for proposed projects in Puerto Rico may consult with the Jacksonville District Regulatory Division by phone (904-232-1177) or by email (SAJ-RD@usace.army.mil). The District's Regulatory web site contains applications and other helpful information for prospective permit applicants.[13] Further, contact information for the Jacksonville District Regulatory Field Office in Puerto Rico is provided below:

Antilles Permits Section
Annex Building, Fundación Angel Ramos
383 Franklin Delano Roosevelt Avenue, Suite 202
San Juan, PR 00918
(767) 289-7040

On the other hand, the US Army Corps of Engineers, through Section 10 of the Rivers and Harbors Act of 1899 (33 USC 403), administers and regulates navigable waters of the US, also referred to as "tidal waters" which are defined as "those waters that are subject to the ebb and flow of the tide and/or are presently used, or have been used in the past, or may be susceptible for use to transport interstate or foreign commerce".

The Mean High Water is defined as "the average of all the high-water heights observed over the National Tidal Datum Epoch." NOAA has twelve tidal stations around Puerto

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[13] USACE Jacksonville District regulatory website: http://www.saj.usace.army.mil/Missions/Regulatory/

Rico, which can be used, for site specific information to establish the local Mean High-Water line[14].

Section 404 of the Clean Water Act (CWA) establishes a program to regulate the discharge of dredged or fill material into waters of the United States, including wetlands. Activities in waters of the United States regulated under this program include fill for development, water resource projects (such as dams and levees), infrastructure development (such as highways and airports) and mining projects. Section 404 requires a permit before dredged or fill material, such as rubble mound or sand may be discharged into waters of the United States. Although the US Environmental Protection Agency regulates the implementation of the CWA, the USACE administers the program and executes permit decisions, and enforces Section 404 permit provisions.[15]

Figure 8 depicts the USACE regulatory jurisdiction of tidal and fresh water and the extent of Section 10 and Section 404 of the Clean Water Act jurisdictions.

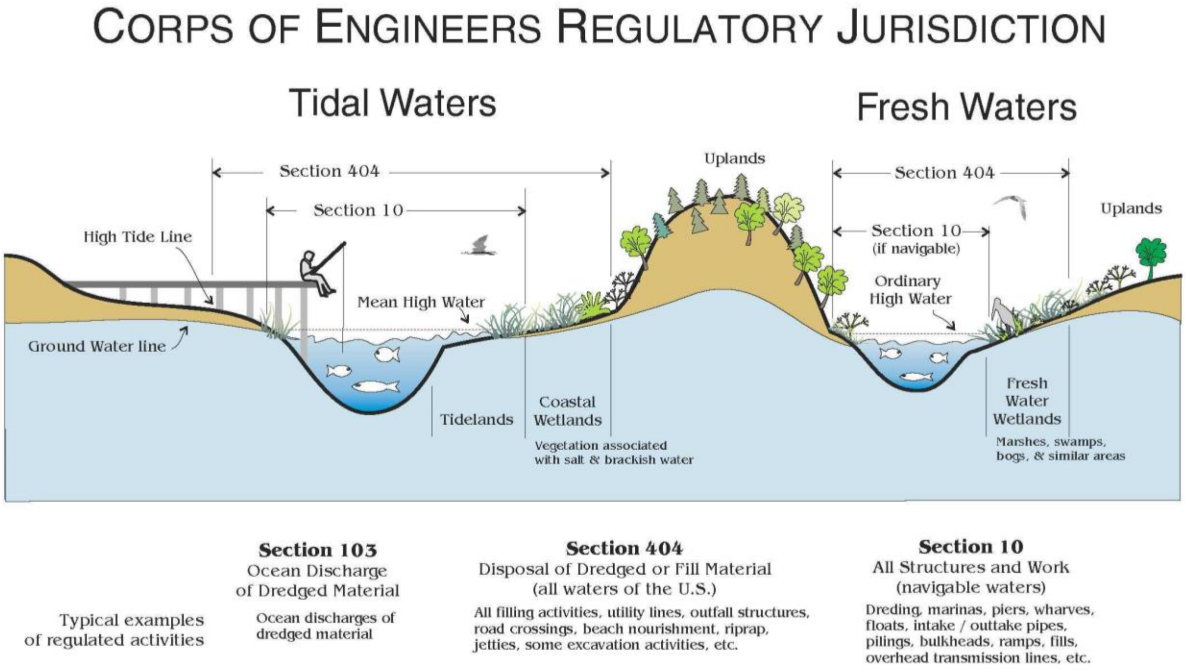

Figure 8. USACE regulatory jurisdiction of tidal and fresh water (USACE, 2019).

As with many states in the US, Puerto Rico has adopted a Joint Permit Application process which intends to integrate and expedite the application and evaluation of new projects or the reconstruction of existing coastal projection structures within jurisdictional waters. This Joint Permit process is led by the PR DNER and the project specific

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[14] NOAA website (https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels)

[15] Find information about Section 404 of the Clean Water Act on the USEPA website at https://www.epa.gov/cwa-404/section-404-permit-program

applications are distributed throughout local and federal regulatory and resource agencies. The latest version of the Joint Permit Application form may be downloaded from the PR DNER website [16], or the USACE website [17].

The planner or engineer preparing this application and managing the Joint Permit process, must be prepared to submit all pertinent baseline studies, and environmental documentation necessary for a thorough and complete regulatory and scientific evaluation by the resource and regulatory agencies involved in the Joint Permit process.

3.3 Local Regulatory Requirements (DNER)

The Puerto Rico Department of Natural and Environmental Resources through Regulation 4860, as amended in 1992, has jurisdiction over the coastal maritime zone out to its jurisdictional limit, or “territorial waters extending seaward from the shoreline of the island of Puerto Rico and from its adjacent islands as it has been or may in the future be modified or altered by separation, erosion, or withdrawal of the sea, out to the marine leagues (or 9 nautical miles)” (DNER 1992). The coastal maritime public domain is defined as “the shoreline and the shore of the rivers including the maritime zone… sensible to tidal action; including those salt-marshes, ponds marshes, estuaries and, generally the low lands bathed by the ebb and flow of the tides, their bed and subsoil; the territorial waters and submerged lands thereunder.”

This regulation also establishes, in Article 5, that privately developed projects within the coastal maritime zone pay an annual concession proportional to the extent and use of the area affected by the project. Not many projects in Puerto Rico, other than privately owned marinas, pay the appropriate annual fees for these concessions.

All projects within the maritime terrestrial zone (MTZ) must apply for a concession for the use of the MTZ, or submerged lands and territorial waters of PR. In certain cases where the integrity or stability of an existing structure is under imminent risk of an ongoing or forecasted threat, the property owner may solicit an emergency permit under the Regulation 4860, Article 16.

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[16] Joint Permit Application at DNER website: (http://drna.pr.gov/formularios/sc-01-solicitud-conjunta-joint-permit/)

[17] Joint Permit Appliation at USACE website: (http://w3.saj.usace.army.mil/permits/RDAvatarPRV201203/languages/eng/pdf/eng4345a.pdf)

4 KEY CONSIDERATIONS AND CRITERIA FOR PLANNERS, ENGINEERS, DESIGNERS, AND EVALUATORS (PLANNING STAGE)

4.1 Planning Approach

Using a systematic approach to the planning of coastal stabilization projects helps one to develop a project that is consistent with the coastal environment, robust in its performance, and cost effective over its project life. This section adapts the comprehensive planning approach provided in the US Navy's Climate Change Planning Handbook (Leidos, Inc. and Louis Berger, Inc., 2017)

The first step in any coastal planning effort is to identify key members of the project team. These typically include:

- **The Owner:** who establishes the site stabilization objectives and applicable physical and financial constraints in the site development process. If the project is of public interest and proposed by a local governmental agency such as a municipality, or a state agency, the applicant is the agency and the permit process is led by the PRDNER. If the project is private, the owner or developer will be the project proponent and applicant and the permit process must commence with a Joint Permit Application.
- **An experienced Coastal or Civil Engineer**: who would advise the owner and who evaluates the features of the coastal segment encompassing the project site and develops alternative stabilization approaches that are compatible with that environment. The Owner should retain a coastal or civil engineer on the basis of specific education and project experience. The American Society of Civil Engineers has established the Academy of Coastal Ocean, Port and Navigation Engineers (ACOPNE) to distinguish individuals who practice in these advanced technical specialties. The academy board certifies applicants as Diplomates of Coastal Engineering (D. CE), indicating that they practice at the expert level of the specialty.[18] The certification is offered only after the applicant demonstrates satisfaction of the academy's detailed listing of education and experience requirements. The selected engineer should have significant knowledge of the unique oceanographic conditions affecting Puerto Rico. If no licensed coastal engineer is available, an experienced civil engineer should be assisted by an experienced physical or coastal oceanographer with significant consulting experience. In addition, the University of Puerto Rico at Mayaguez has an Ocean and Coastal Engineering research program with several highly qualified Coastal and Ocean Engineers, Physical Oceanographers and Scientists who are experts at evaluating coastal and oceanographic conditions.
- **A Marine Biologist:** who would identify plant and animal species and benthic communities in the project general area and assists the engineering design team in the development of alternatives that minimize the impacts to those species and habitats. Typically, a marine biological baseline survey and study is conducted to assess and document the conditions of the site.

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[18] A listing of coastal diplomates is available at http://www.acopne.org.

- **An Environmental Professional**: with experienced in coastal and marine resources specific to the project area, and familiar with the local and federal regulatory climate. The environmental professional will work with the engineers and biologists to identify avoidance, minimization, and mitigation options for the project. The Owner should retain an environmental professional on the basis of specific education and project experience. The Academy of Board Certified Environmental Professionals administers the Certified Environmental Professional (CEP) Program and certifies only those professionals that demonstrate satisfaction of the academy's detailed listing of education, recommendations, and application requirements[19]. The PRDNER Coastal Zone Management Program staff is also available to advise the Owner on applicable local and federal law and regulations.
- And other Specialty Professionals such as:
  - Bathymetric and topographic surveyors familiar with the delineation of the maritime zones, and coastal datum.
  - Geotechnical engineers familiar with marine and coastal processes such as erosion, scouring, and liquefaction.
  - Oceanographers with a specialty in wave and ocean circulation modeling and ocean observing
  - Geologists or geomorphologists with expertise in beach dynamics
  - Regulatory specialists familiar with the local and federal regulatory framework.

4.2 Planning Stages

The planning stages of a coastal engineering project can be categorized into four stages (Figure 9). Each stage is described in detail in the following subsections.

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[19] http://www.abcep.org.

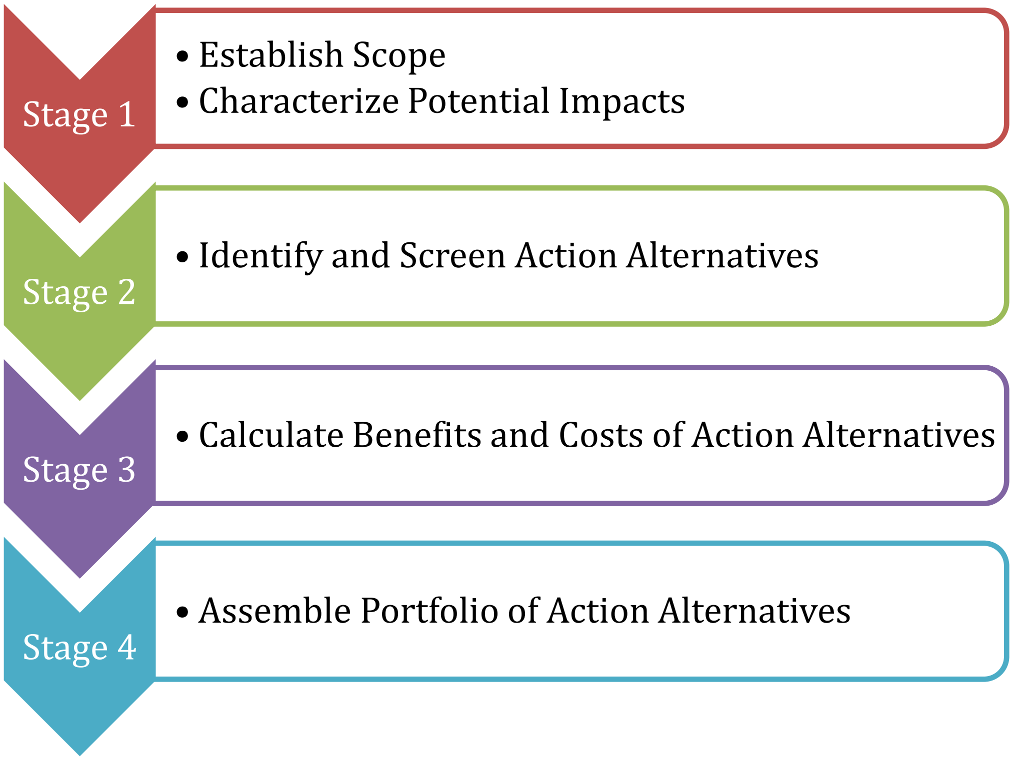

Figure 9. The four planning stages to a coastal engineering project.

4.2.1 Stage 1: Establish Scope and Characterize Potential Impacts

This stage sets up the preliminary research steps needed to develop a concise statement of the coastal problem such as flooding, erosion, wave impacts, etc. that will be addressed by the planning effort. It is necessary to establish a clear scope by examining and defining parameters such as the geographic extent of the subject area, the proposed project lifespan, the local coastal processes and hazards of interest, climate phenomena and others. The development of the assessment also considers the impacts of these parameters on existing and planned infrastructure on the project site and potential impacts downstream or down the coast from the project.

The assessment scope includes the following parameters:

- Focus – all or a portion of the site. Define the limits of the project and its extents. Is this a localized problem or a regional issue?
- Hazards – flooding, waves, shoreline erosion (onshore/offshore vs. longshore)? What are the driving forces and engineering parameters to be considered?
- Weather/climate phenomenon – sea level change, storm surge?
- Decisions - investment decision, risk management plan, natural resource management plan?
- Information – Available maps? Site surveys? Historical records? Databases? Projections?

- Timeframe – how far into the future is your project expected (or required) to perform?
- Additional direction/criteria – are there other requirements associated with the project?

4.2.1.1 Identify and Evaluate Information

This step reviews the full range of the physical data compiled for the site and its vicinity to determine if it is sufficient for analysis or requires supplemental investigations or surveys. For example, vertical land elevation is an important factor in understanding the reference datum and assessing flood risks.

There are several sources of data that are applicable to the design of coastal stabilization facilities. The following sections outline some of the major ones.

4.2.1.2 Describe and Characterize Impacts

At this stage, the impact analysis is generic and can consist of damage characterizations such as frequent chronic low-level flooding, occasional significant flooding[20], shoreline erosion, scouring, etc.

4.2.1.3 Develop Problem Statement

A problem statement succinctly defines the type and magnitude of potential impacts and issues to be addressed. A problem statement contains the following components:

1. Infrastructure scope
2. Hazard
3. Timeframe
4. Weather or climate phenomena
5. Time slice and climate scenario
6. Description of the potential impacts on infrastructure types as a result of analysis

4.2.2 Stage 2: Identify and Screen Action Alternatives

4.2.2.1 Identify Potentially Suitable Adaptation Actions

The development of potential suitable adaptation actions requires the analysis of the meteorological, oceanographic and geomorphic characteristics of the project site and its vicinity. The US Army Corps of Engineers (USACE) has developed a comprehensive Coastal Engineering Manual (CEM) (USACE, 2002). This manual provides the basic principles of coastal processes, methods of computing coastal planning and design parameters, and guidance on how to formulate coastal flood studies and shore protection projects. The CEM is available online and is comprised of six Parts and an Appendix. The CEM is regularly updated by the USACE and is a reliable compilation of current coastal engineering practices.

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[20] ESRI, Ecological Marine Units, URL: http://www.esri.com/ecological-marine-units

There are some basic steps involved in the estimation of coastal risks and the assessment of infrastructure alternatives for risk reduction and climate adaptation. The CEM provides detailed guidance in performing the analyses involved in each of the steps. These steps are:

> *Estimate Offshore Hydrodynamics* – The analysis starts with oceanographic conditions that generate offshore wind-generated waves. Advanced wave generation models are available to support this analysis.
>
> Coastal analyses also require evaluation of wind, waves, mean sea level, tides and storm surge. The key result of this step is the determination of average and extreme offshore conditions in the project region, which will be used to develop sound design criteria.
>
> *Estimate Nearshore Hydrodynamics* – Waves propagating from deep to shallow waters interact with the configuration and water depths of the water basin that they travel through. These interactions result in wave refraction, diffraction, dissipation and shoaling as well as other energy transfer processes. A key result from this step is the characterization of nearshore wave heights, directions and wave periods. These parameters will also be used to develop sound design criteria for locating and sizing offshore wave energy dissipation features.
>
> *Estimate the Effects of Coastal Stabilization Elements on Hydrodynamics* – The nearshore waves interact with the proposed coastal structures or nature-based protective measures, which result in wave changes such as wave attenuation and, in some cases, wave reflection, refraction and/or diffraction. The tools to assess these interactions vary with the character of the coastal stabilization elements. The CEM and guides in Annex 4 provide guidance.
>
> *Estimate Onshore Flooding or Erosion –* Wave energy that penetrates landward of the coastal stabilization elements can contribute to flooding and/or erosion. For flooding, the key result for this step is an assessment of onshore flooding relative to the storm frequency. For example, the FEMA base flood has an annual frequency of occurrence of 1%, or a mean recurrence interval of 100 years. This will assist in establishing base elevations and final design elevations.

4.2.2.2 Identify Benefits and Limitations

Based upon the analyses of the previous step, one can develop a table of benefits and limitations for each of the considered action alternatives.

4.2.2.3 Evaluate Feasibility

The evaluation of a potential action alternative involves considerations such as environmental constraints, permitting and regulatory limitations, constructability, availability of materials, access, project costs and schedule.

4.2.2.4 Evaluate Appropriateness

This step addresses the following questions:

1. Is the proposed action alternative consistent with development plans?
2. Is it acceptable to other stakeholders?
3. Is it a proportional response to the anticipated impacts?

4.2.2.5 Characterize Approach to Decisions under Uncertainty

1. Problem – Identify owner, agency/municipality and provide key information
2. Diagnosis Definition:
   - 2.1 Trends
   - 2.2 Sediment behavior (pre-sed budget)
   - 2.3 Position – protected, reefs, other
   - 2.4 Wave climate/winds – MetOcean Studies
   - 2.5 Beach morphology – nearshore and upland
   - 2.6 Type of sediment grain – grain size type, compatibility analysis
     - 2.6.1 Reefs, colonized bedrock
     - 2.6.2 Dunes
   - 2.7 Mangroves
   - 2.8 Wetlands
3. Identify options to address problem
   - 3.1 Dissipate energy, wave action (offshore), detached, submerged
   - 3.2 Protect
     - 3.2.1 Revetment
     - 3.2.2 Reinfoced Dunes
     - 3.2.3 Sea wall – non-vertical, stepped, sloped, wave deflectors
   - 3.3 Nourishment
   - 3.4 Vertical Adaptation – increased height
   - 3.5 Planned Retreat – abandoned structures

4.2.3 Stage 3: Calculate Benefits and Costs of Action Alternatives

To calculate the benefits and costs of potential alternatives, one must assess the expected or averted damages that are attributable to the implementation of the alternatives. For small projects, the damage assessment is relatively straightforward, since only a few upland facilities may be affected, and their value is known to the project's Owner. For larger more regional projects, tools such as FEMA's HAZUS flood model[21] are more appropriate for consideration. The flood loss estimation methodology consists of two modules that carry out basic analytical processes: flood hazard analysis and flood loss estimation analysis. The flood hazard analysis module uses characteristics such as frequency, discharge and ground elevation to estimate flood depth, flood elevation and

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[21] Federal Emergency Management Agency, (FEMA). Hazus Flood Model, URL: https://www.fema.gov/hazus-mh-flood-model

flow velocity. The flood loss estimation module calculates physical damage and economic loss from the results of the hazard analysis.

4.2.4 Stage 4: Assemble Portfolio of Action Alternatives

- Environmental and Site-specific Considerations
- Meteorological and oceanographic conditions: waves, winds, currents
- Biological or environmental conditions (coral, sandy, estuarine, wetlands)
- Possible solutions for select scenarios (emergency response – basic; moderate; higher end – nature based)
- Necessary studies for each solution
- Tools and mechanisms to support decision-making
- Regional and municipal planning considerations (explore why it is important to consider regional context)
- If there are other problems nearby, there is continuity to solutions that are applied and no adverse impacts downdrift
- To understand problem/solution from a regional planning context
- Key Considerations and Criteria for Engineers (Analysis and Development Stage)

4.3 Summary of Outputs of Planning Stage

- Minimum technical requirements (emergency response – basic; moderate; higher end – nature based)
- Engineering analysis
- Feasibility
- Design
- Implementation and Construction
- Best practices – international vs. local

5 KEY CONSIDERATIONS AND CRITERIA FOR ENGINEERS (CONSTRUCTION STAGE)

Case Studies either separate section or woven throughout.

Flowchart/Decision Tree Summary (for each major section and then summary at end (conclusion)

5.1 Site Assessment Approach for Existing Coastal Projects

The following section presents a typical procedural approach to assess a coastal project or site which may have been eroding or become unstable due to exposure to wind, waves, or currents.

This approach has been developed based on common situations frequently found in urban beaches along the Puerto Rico shorelines.

Resources include the USACE Engineering and Design Manual EM 1110-2-1614 - Design of Coastal Revetments, Seawalls and Bulkheads (1995) which provides detailed design guidelines for revetments, seawalls and bulkheads.

As outlined in Section 4, the initial assessment needs to define the problem and cause, if possible.

5.1.1 Localized Shoreline Erosion Patterns

Shoreline erosion is a natural process that is often accelerated by human intervention. Many beaches on the north and west coasts of Puerto Rico are naturally nourished by the flow of sediments carried by rivers during rainstorms. As water resources needs increase, dams are constructed which trap sand upstream in the reservoirs, and rivers are channelized which limits sediment input from bank erosion, resulting in a deficit of sand naturally nourishing the beaches. Also, hardening the shoreline with vertical seawalls and revetments prevents the contribution of sediments onto the beaches. However, many urban coastal areas have already been impacted, and erosion has accelerated due to poor design and construction, lack of maintenance to these structures, lack of maintenance to the beaches, continued natural coastal erosive forces (wind, waves, currents) and reoccurring extreme climatological events (tropical and winter storms and hurricanes).

Hurricanes Irma (September 6, 2017) and Maria (September 20, 2017) caused significant shoreline erosion in many areas along the east coast from Patillas to Yabucoa, and along the northwest and west coasts from Aguadilla to Cabo Rojo. Several sections of developed coastlines were severely eroded, exposing ill designed and constructed seawalls, gabion walls and foundations, resulting in structural damages and catastrophic failures of not only these structures but the buildings and homes they intend to protect. Examples of failed structures have been documented around the island of Puerto Rico's shoreline and most severely noted in the west, the north, and the east coast.

5.1.2 Gabions

Gabions are gravity structures made out of rocks ranging between 6 to 8 inches, contained in steel wire mesh cages of different sizes and dimension. Gabions are successfully applied in riverine and lake applications where saltwater and corrosion are not a problem. However, gabions have been historically used in Puerto Rico for the past four decades in coastal engineering applications with negative results. And yet, some civil engineers and contractors continue to use gabions since the cages and aggregate are readily available and inexpensive.

If there are gabions on a coastal environment, they should be removed and replaced with suitable shoreline protection. The corroded steel wire mesh poses a safety threat and the rocks are individually too small to withstand wave forces and currents. They typically fail and result in a hazardous condition for beach goers as they encounter rusted and sharp objects which can cause injury to the public.

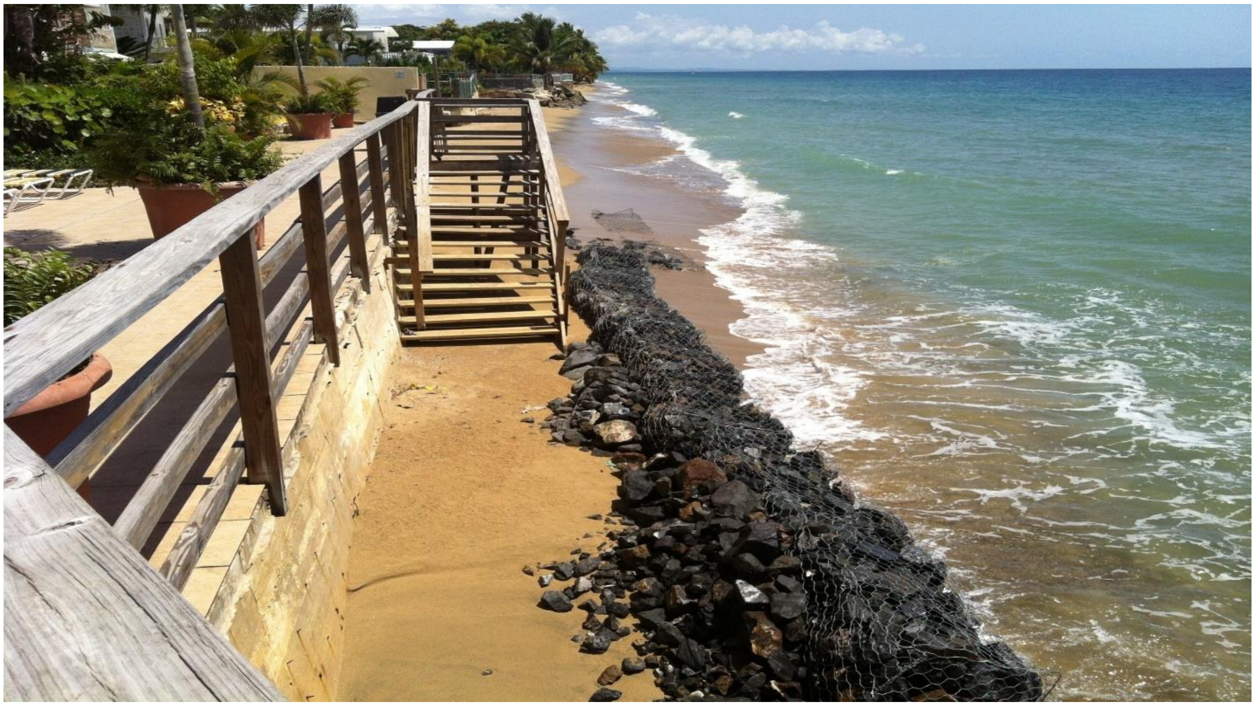

Figure 10. Failed gabions along shoreline in Córcega, Rincón. Wire cage mesh has broken open, posing safety threat, and releasing rocks onto beach.

Figure 11. Broken wire mesh of gabions used as foundation material for concrete walkway at Punta Isla Verde, San Juan. Photo taken September 21, 2018.

The wire mesh containing the rock must be removed, if it has not been corroded completed. The existing gabion rocks may be used as filter rock or to regrade the slope if it is protecting a bluff or an eroded section of beach. A non-woven geotextile should be placed as a filter fabric between the fine sand or soil, and the filter rock and armor rock should be placed over the filter fabric.

Figure 12. Gabions used as coastal protection for walkway in Punta Isla Verde, San Juan, Puerto Rico. Top photo taken on September 21, 2018 and bottom photo taken on October 25, 2018.

Some recent application of gabions has been installed with a non-ferrous high-density polyethylene (HDPE) material such as Tensar (copyright symbol) panels. However, these panels are assembled with plastic tie wraps which are also sensitive to UV degradation and fail within a few years, especially if they are exposed to sunlight.

Examples of poorly applied synthetic gabions can be found at the PREPA Subsea Cable Landing at Punta Arenas, Vieques, and the Isla de San Juan Bluff Stabilization Project at Ponce de León Ave. between Parada 7 and El Capitolio.

Figure 13. Synthetic gabions for San Juan Bluff Stabilization Project in Old San Juan, Puerto Rico. Photo taken on October 25, 2018.

5.2 Alternatives for Coastal Hazards Mitigation

Humans cannot prevent these extreme natural events beyond the already anthropogenic impacts that have accelerated climate change. There is no single solution to the problem of coastal erosion considering the variability of conditions, and the dynamic nature of the shoreline.

However, the USACE has classified alternatives or solutions to coastal hazards in five functional classes of engineering or management strategies (USACE, 2002). These mitigating alternatives are presented in Table 1. A flowchart for alternative selection is presented in Figure 14.

Table 1.Possible Mitigating Alternatives for Puerto Rico

Functional Class	**Approach Type**
Do nothing	No intervention
Beach stabilization and restoration (non-structural, nature based)	Beach nourishment Berm restoration Dune restoration and vegetation
Beach protection structures	Emergent breakwaters (including headlands) Artificial reefs and submerged breakwaters Sand Bags or Sand filled Geotubes® Sills and perched beaches Groins
Armoring structures	Revetments Seawalls and bulkheads
Adaptation and accommodation	Flood proofing Zoning Retreat
Combinations	Structural and stabilization/restoration Structural, restoration and adaptation

FLOWCHART 3: ALTERNATIVE SELECTION

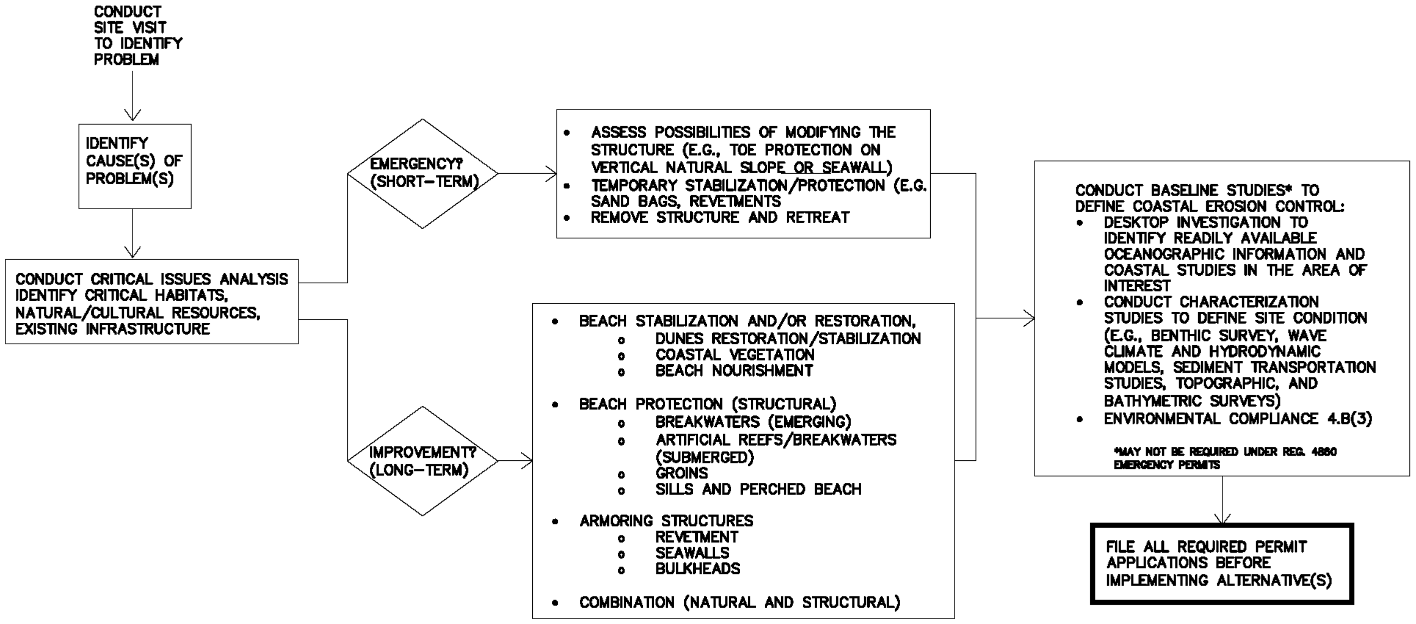

Figure 14. Flowchart 3 for Alternative Selection.

5.2.1 Do Nothing

The “do nothing” alternative is always a possibility if the decision maker with jurisdiction over the property,

5.2.2 Beach Stabilization and Restoration

5.2.2.1 Beach Nourishment

Beach nourishment is primarily the importation of sandy material onto an eroded beach to create a wider beach or recover the beach to a pre-eroded condition. Beach nourishment has many economic benefits and provides for a certain level of shoreline protection as it represents a buffer zone that absorbs and dissipates wave energy. However, given its related costs and vulnerability to extreme wave conditions and erosion, these projects are sometimes coupled with other structural (e.g., groins, breakwater, revetments, etc.) or non-structural measures (e.g., wetlands, living shorelines, dune vegetation, sand fences, etc.) Another important consideration when designing a beach nourishment project is the over-building of the berm and the dune to result in the ultimate design beach width under an equilibrium condition.

Beach nourishment projects are typically driven by federally funded programs in the US and led by the USACE. The USACE has not conducted a beach nourishment project in Puerto Rico to date, but in August 2018, commenced a feasibility study to identify potential beach nourishment projects in eroded shoreline reaches, in particular near the San Juan metropolitan coastline. These high cost projects need to be justified by the federal government through a Benefit Cost Analysis, which proves that the capital cost of the project has a tangible public economic benefit, and therefore it is in the best interest of the US to invest federal funds.

Beach nourishment projects have components or features which may include: the berm, the dune, the feeding portion of the dune, the nearshore berm, and stabilization of the dune with vegetation or other means.

5.2.2.2 Berm Restoration

The berm is the highest point on the beach profile and in beach nourishment projects it is used as the elevation of maximum runup to prevent or mitigate flooding. Sometimes during certain high wave conditions, the lower portion of the berm is translated inland by wave uprush causing an increase in berm height and a steeper beach profile, which often results in a false sense of protection. Planting native coastal vegetation along the berms is a good practice and provides protection against aeolian erosion.

5.2.2.3 Dune Restoration

The dune is the naturally occurring ridge that is distinguished between winter and summer beach profiles, and which often serves as protection during extreme high tides and storm surge and becomes the feeding source of the beach. In beach nourishment projects where sand is transported either by land or pumped from a dredge, the dune should be oversized and its finished elevation should be above the limit of wave runup under high seas conditions, and of sufficient width.

CEM, Chapter 4 – Beach Fill Design

5.2.3 Beach Protection Structures

5.2.3.1 Emergent Breakwaters

The U.S. Army Corps of Engineers has been designing breakwaters all over the U.S. since the early 20th century. Rubble mound breakwaters are can be offshore detached or attached structures intended to dissipate wave energy long before waves reach the shoreline. Most breakwaters in Puerto Rico are used as offshore protection for marinas and harbors and there are some instances where breakwaters have been constructed for beach and shoreline stabilization.

Figure 15. Example of offshore detached breakwater at El Morro in Old San Juan.

Breakwaters are typically designed and constructed with native in-situ rock, where available. Puerto Rico's geology has many sources of suitable rock material to be used for breakwater design and construction. There are many quarries around the island that produce this type of material, however it is imperative to ensure that the material has the proper hardness and durability characteristics required to sustain wave action and abrasion encountered in high energy environments. The primary parameters to be considered for the suitability of the material are size, density or specific weight, hardness, and abrasion.

Emergent breakwaters are designed to resist overtopping by wave action and allow little or no energy transmission throughout the structure. Therefore, their crest elevations are significantly higher than mean sea level and always visible from the shoreline. Design guidelines for breakwaters can be found in the Coastal Engineering Manual.

Some emergent breakwaters can be designed and constructed to incorporate ecological enhancement features typical of artificial reefs.

Figure 16. Example of offshore detached breakwaters in Dorado.

5.2.3.2 Artificial Reefs & Submerged Breakwaters

Artificial reefs and submerged breakwaters may be used in nearshore waters to partially dissipate wave energy and induce wave braking at some distance from shore. These structures are often designed with multifunctional elements to enhance the potential environmental benefits of attracting and aggregating fish, mollusks, crustaceous and other marine species. One of the features that makes the artificial reefs more effective than conventional breakwaters is the increased porosity in the aggregate and armoring. Also, locally available karst material with naturally occurring crevices and pockets may be utilized to support small fish aggregation and enhance the viability of coral adhesion.

Figure 17. Naturally occurring crevices and pockets in aggregate suitable for artificial reefs and submerged breakwaters.

These low-crested structures (where the top of the structure is at or just below the mean sea level) are more effective in coastlines where tidal ranges are small such as throughout the Caribbean. However, their low crested nature allows the partial transmission of wave energy and therefore are not as effective as emerging breakwaters and artificial islands which absorb most of the wave energy. Artificial reefs and submerged breakwaters can also be used and configured to dissipate and redirect dangerous rip-currents that occur in several key location along the northern and eastern shoreline of PR.

The development and conceptualization of these structures follow the conventional planning, permitting and design standards specified in the CEM, Vol. V. Local considerations for these types of structures would include water depths and bathymetry, proximity to the shoreline, substrate, and geomorphology.

5.2.3.3 Sand Bags or Sand Filled Geobags

Sand bags and sand filled Geobags have been commonly used in the US and in Puerto Rico as immediate or short-term shoreline protection methods. There are several manufacturers whose products are available in the internet. Some of the more robust geotextile include UV resistant pigments, PVC coatings, and other textures intended to extend the life of the material. However, these systems, if exposed to sunlight and direct wave impact, tend to eventually degrade. These applications are effective as buried scour protection, or as a buried or submerged retaining structure. The formulation of these applications require the standard coastal analysis and design process utilized for revetments and breakwaters which includes understanding the littoral sand transport mechanisms along the particular site, establishing design wave criteria, elevations, slopes and proper sizing. Although sandbags and Geotubes®, or similar are commonly applied as emergency stabilization measures, if properly designed and installed, they can last several years, especially if they are buried or only seasonally exposed to abrasion and ultraviolet rays.

Figure 18. An eroding shoreline at Marbella Club, Palmas del Mar (left photo). Sand filled geotubes were placed along the shoreline in January 2016.

Figure 19. Erosion of the shoreline around geobags at Marbella Club, Palmas del Mar in December 2016, approximately 1 year after construction (left photo). Erosion around geobags at Marbella Club after Hurricane Maria (right photo).

Parcelas Suarez, Loiza

5.2.3.4 Sills and Perched Beach

The perched beach concept is a sill or a submerged structure parallel to shore intended to act as an underwater dam to retain sand from migrating offshore. These structures can be rubble mound or geobags and are typically effective in smaller coves and relatively shallow waters. Depending on the distance from shore, water depth and crest depth, the perched beach concept may induce wave braking and also act as a wave energy absorption devise or wave attenuator. However, given the fact that it is a shore parallel device, it does not interrupt littoral as opposed to shore perpendicular groins. The perched beach concept is also effective when coupled with a beach nourishment project.

5.2.3.1 Groins

Groins, also referred to as jetties, are shore-perpendicular structures, often equidistantly spaced, that are designed to trap longshore sand transport. Longshore sand transport is a naturally occurring phenomenon caused by shore-parallel or localized currents that transport sand along, or parallel to the shoreline in one direction or the other depending on the incident direction of the incoming short-period wind waves and/or longer period swells.

The planning and location of groin fields should be carefully analyzed and designed for effectiveness, as they trap sand upstream and deplete the beach from sand downstream. Generally, these structures are placed in closed littoral cells or shoreline reaches that present a certain degree of seasonal equilibrium which maintains a balanced sediment transport budget.

Groins are not typically effective in shorelines where onshore/offshore sediment transport are the primary cause of shoreline erosion.

An example of a small groin can be found at the end of Calle Condado in Condado along the beachfront in front of La Concha Resort.

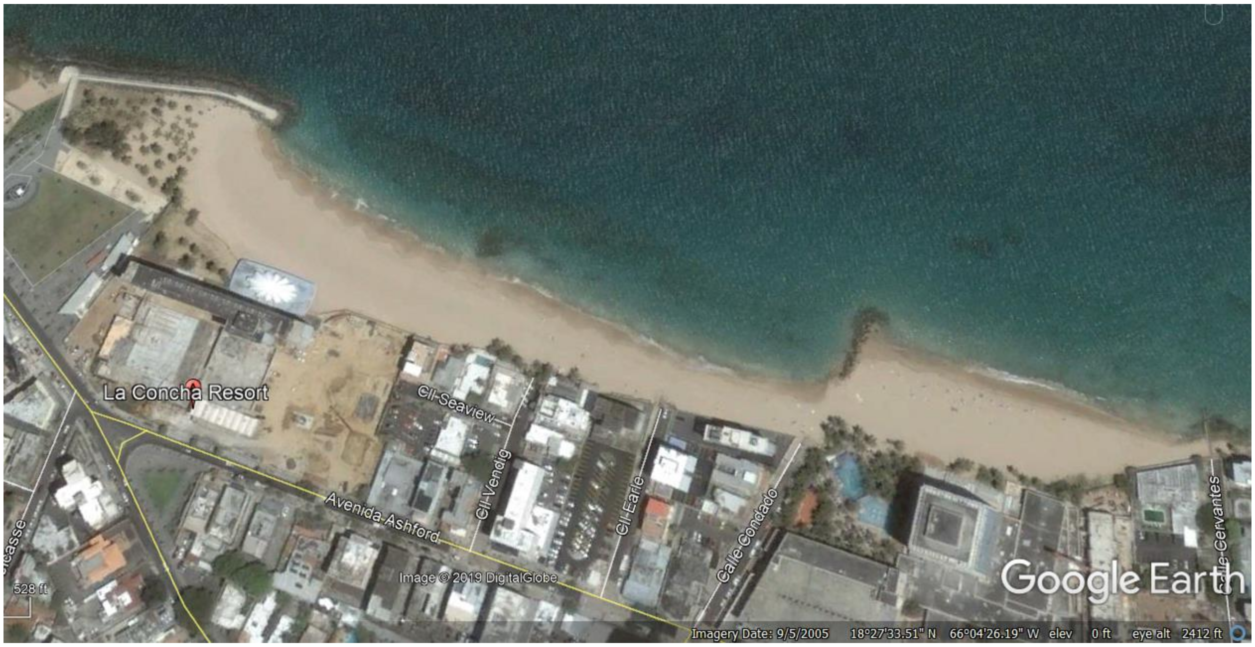

Figure 20. Groin in Condado, Puerto Rico. Google Earth Imagery September 5, 2005.

5.2.4 Armoring Structures

Many shoreline protection and armoring structures in Puerto Rico are either gabion walls, revetments, vertical seawalls or bulkheads or non-engineered makeshift structures. In many instances, these structures are inappropriately applied and/or designed and often times result in more damage.

Properly designed armoring structure must follow the engineering analysis and procedures specified in the Coastal Engineering Manual (CEM). The primary forces and scouring are caused by wave impact, wave induced currents and wave runup. Generally, these structures are constructed with locally available quarry rock, stacked on a slope no steeper than 1.5 horizontal to 1 vertical. Ideally, a milder slope such as 2 horizontal to 1 vertical is more stable, however, spatial and elevation considerations must be accounted for by the engineer. Revetments can be effectively placed in front of existing vertical seawalls to dissipate direct wave impact and reduce the reflected wave height, which would otherwise combine with the incoming incident wave.

In addition, revetments can be used as scour protection devices to stabilize the toe of existing vertical structures which in their absence would continue to erode vertically and eventually undermine the wall and cause catastrophic failure.

Examples of these unprotected vertical structures which have failed due to undermining and scouring can be found around the island. An example of an unprotected vertical structure that lead to the development of sinkholes on the landward side of the seawall is shown in Figure 21.

Figure 21. Unprotected vertical seawall in San Juan Puerto Rico.

As alternatives to conventional quarried rock materials, and in areas where these materials are not readily available due to their local geomorphological characteristics, other precast armor units (e.g., dolos, Tetrapods, Accropods, tribar, Core-Loc, A-jacks, etc.) may be used. However, that is not the case in Puerto Rico due to the prevalence of quarries on the island with suitable rock for armoring structures.

The primary design considerations for revetments are the design wave height (typically referred to as the significant wave height), the toe elevation and scour protection, the fore slope, the crest elevation and the thickness of the section. To maintain a stable cross-section, it is important to provide a filter layer and/or a geotextile to maintain the fine grain material from filtering through the armor rock. It is also very important to calculate the size of the armor rock in accordance with the expected significant wave height at the location. As a minimum, the design must resist conditions which have a 50% of being exceeded at any time throughout the economic life of the project, without suffering at any time a catastrophic failure.

A simple and commonly used method to measure the stability of the armor units was developed by Hudson (1961), which takes into account the weight of each armor unit, the specific weight of the rock, a monochromatic wave height, a stability coefficient and the specific weight of salt water. Van der Meer and Pilarczyk (1987) also derived stability equations from extensive laboratory tests for plunging breakers and for surging or non-breaking waves (USACE, 1995). These equations should be used by the design engineer to ensure that the size and gradation of the armor units are appropriate to the wave climate and site conditions.

Depending on the location, elevations, tidal conditions, and sea state, the revetment may be subject to breaking waves or wave run-up, or not exposed to wave action. In all instances, geotechnical or geomorphological conditions should be taken into consideration.

5.2.4.1 Revetments

Revetments are typically designed to stabilize a slope or an eroded section of shoreline and are generally governed by hydraulic criteria

Figure 22. (Left photo) Eroding shoreline prior to bank stabilization at Palmas del Mar. (Right photo) Development of Plaza del Mar revetment, Palmas del Mar

Seasonal beach profiles must also be taken into consideration when designing a coastal revetment. Typically, winter beach profiles reveal a lower toe elevation and hence should be considered when calculating the thickness and bottom elevation of the toe protection. That is one of the reasons why it is so important to conduct a topographic and bathymetric survey along the entire extent of the eroded shoreline. The survey will serve as the baseline condition for the design of the revetment or shoreline protection measure.

5.2.4.2 Seawalls and Bulkheads

The terms seawall and bulkhead are often used interchangeably, but generally bulkheads are upland retaining walls which are designed to resist wave impact under certain conditions, and seawalls are primarily designed to resist wave impact but also retain some soil to assist in resisting wave forces. Seawalls are also exposed to hydrostatic pressures conditions such as in marinas and harbors.

Generally, primary considerations for these vertical structures are geotechnical conditions and hydraulic factors. They can be cantilevered (deep foundation), or anchored with tie backs, or gravity. For cantilevered and anchored walls the passive earth pressure zone is maintained to prevent overturning. Gravity walls resist sliding through the frictional resistance at the base of the wall (USACE, 1995).

Besides the standard design considerations of vertical retaining structures, when exposed to waves and currents, these walls reflect the incoming wave energy (breaking, non-breaking and broken), and experience scouring along the toe of these structures. This phenomenon is commonly observed in coastal bulkheads along the Puerto Rico shoreline and rarely these structures are designed with scour or toe protection. There are many instances along the Puerto Rico shoreline where scour protection is required to protect the existing structure and mitigate the potential erosive effects downstream or on adjacent properties. USACE (1995) also provides guidelines for such scour protection measures, but in principle, the toe protection will avoid the structure from undermining, and will act as an energy dissipating element, thereby reducing reflection and potential downdrift effects.

This toe or scour protection measure should be implemented whenever vertical coastal protection structures are observed under wave action

5.2.5 Adaptation and Accommodation

Puerto Rico's shoreline along the east, north and west coasts are most vulnerable to prevailing and periodic erosive events that result coastline erosion and waterfront structural damages, specially during hurricane season. Means of adaptation may include partial structural reinforcement of existing structures, installation of scour protection (rip-rap along the toe of vertical seawall, and increase the height or base flood elevations. In some instances, for example, raising the elevation of a coastal roadway or highway may be a way to adapt to increase water levels resulting from stronger hurricanes and sea level rise.

5.2.6 Combinations

Combining structural and non-structural measures should also be considered when developing coastal projection projects and alternatives. These combinations such as structural measures (breakwaters, artificial reefs, groins, etc.) with beach nourishment or reinforced sand dunes or living shorelines often result in more resilient and sustainable projects, which to a certain extent become more palatable to regulatory and resource agencies at the local and federal levels.

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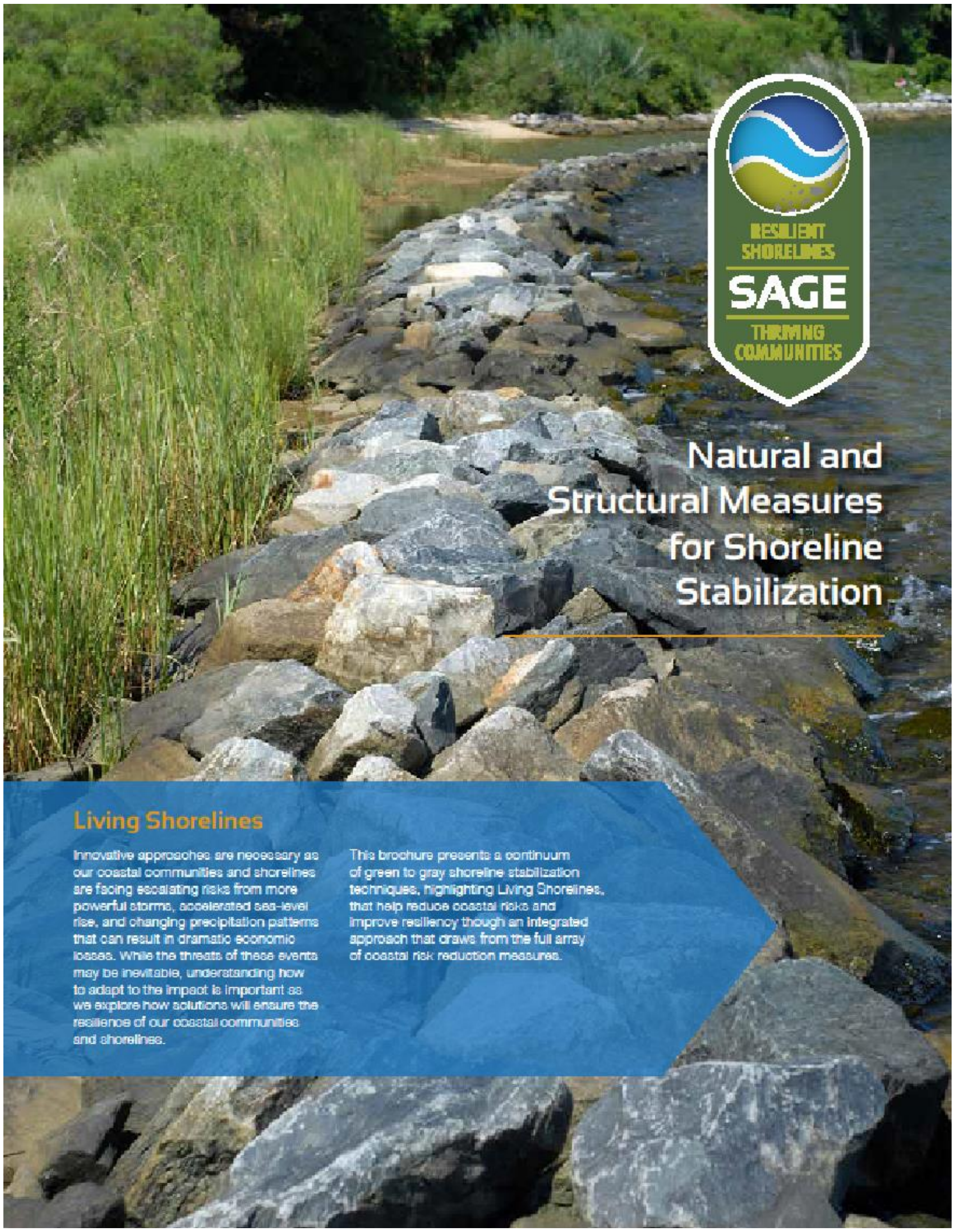
ANNEX 1

SAGE BROCHURE

NATURAL AND STRUCTURAL MEASURES FOR SHORELINE STABILIZATION



RESILIENT SHORELINES
SAGE
THRIVING COMMUNITIES

Natural and Structural Measures for Shoreline Stabilization

Living Shorelines

Innovative approaches are necessary as our coastal communities and shorelines are facing escalating risks from more powerful storms, accelerated sea-level rise, and changing precipitation patterns that can result in dramatic economic losses. While the threats of these events may be inevitable, understanding how to adapt to the impact is important as we explore how solutions will ensure the resilience of our coastal communities and shorelines.

This brochure presents a continuum of green to gray shoreline stabilization techniques, highlighting Living Shorelines, that help reduce coastal risks and improve resiliency though an integrated approach that draws from the full array of coastal risk reduction measures.

ANNEX 2

DEFINITIONS

Coastal Engineering: One of several specialized engineering disciplines under civil engineering. It includes the physical sciences and engineering affecting a coastal area. It requires the understanding and knowledge of several technical disciplines to develop solutions to problems associated with natural and human created changes in the coastal zone, the structural and non-structural mitigation of these changes, and the positive and negative impacts of possible solution to problem areas on the coast. Coastal Engineers may utilize contributions from the fields of geology, meteorology, environmental sciences, hydrology, physics, mathematics, statistics, oceanography, marine science, hydraulics, structural dynamics, naval architecture and others in developing an understanding of the problem and a possible solution. The Coastal Engineer much consider the process present in the area of interest such as:

- Environmental processes (chemical, ecological)
- Hydrodynamic processes (wind, waves, water level fluctuations, and currents)
- Seasonal meteorological trends (hurricane season, winter storms)
- Sediment processes (sources, transport paths, sinks, and characteristics)
- Long-term environmental trends (sea level rise, climate change)
- Social and political conditions (land use, development trends, regulatory laws, social trends, public safety, economics)

Harbor works, navigation channel improvements, shore protection, flood damage reduction, and environmental preservation and restoration are the primary areas of endeavor.

ANNEX 3

RESOURCES FOR EACH STAGE

A-3.1 Resources for the Planning Stage

The evaluation of all relevant environmental and site-specific considerations involves the compilation and evaluation of an extensive list of variables. These include:

- Topography and bathymetry
- Normal and extreme winds
- Tides and currents
- Storm surge and waves
- Sea level rise
- Other oceanographic parameters
- Coastal sediment characteristics
- Marine biological resources

Topography and Bathymetry

Land elevations are referenced to geodetic datum levels that define a fixed plane that is uniform over large distances. Tidal datum levels are very localized since they are strongly influenced by coastal configuration features. Developing accurate site-specific relationships between local tidal datum levels and geodetic datum levels is critical to a coastal project's success.

The National oceanic and Atmospheric Administration (NOAA) has developed a program to assist in this area called VDatum[22]. VDatum is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datum levels. It allows users to convert their data from different horizontal/vertical references into a common system and enabling the fusion of diverse geospatial data into the desired reference levels.

NOAA's Digital Coast[23] website is a source for a variety of coastal data types. Available data bases include data from Light Detection and Ranging (LiDAR) bathymetric and topographic surveys, sea level rise data and numerous other datasets on coastal features and resources. The US Geological Survey has also compiled a national topographic mapping database[24] that provides elevation and shoreline data.

Normal and Extreme Winds

The American Society of Civil Engineers has developed a widely adopted standard[25] for loads on structures that include environmental loads associated with wind, flood, seismic

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[22] NOAA, Vertical Datum Transformation, URL: https://vdatum.noaa.gov/

[23] NOAA, Office of Coastal Management, Digital Coast website, URL: https://coast.noaa.gov/digitalcoast/?redirect=301ocm

[24] US Geological Survey (USGS), The National Map, US Topo, URL: https://nationalmap.gov/ustopo/

[25] American Society of Civil Engineers (ASCE), Minimum Design Loads for Buildings and Other Structures, ASCE Standard 7-16, URL: http://www.asce.org/templates/membership-communities-committee-detail.aspx?committeeid=000009162360

and other conditions that may be applicable in the design of coastal stabilization elements. Wind speeds from the ASCE 7 Standard are also available on a website[26] that allows the user to obtain the design wind speeds for specific areas defined either by address or geographic coordinates. The site provides 3-second gust wind speeds with mean recurrence intervals (MRI) of 10, 25, 50 and 100 years. Standard adjustments allow modifications to other durations and MRIs.

NOAA's historical hurricane tracker site[27] provides a tool to identify, show tracks and provide details in the tropical storms and hurricanes that have passed through a user-selected window around a site of interest. The data can be useful in hindcasting wind and wave conditions from historical storms.

NOAA's National Centers for Environmental Information, NCEI[28] (formerly National Climatic Data Center) is responsible for "…preserving, monitoring, assessing, and providing public access to the Nation's treasure of climate and historical weather data and information."

Tides and Currents

NOAA's Center for Operational Oceanographic Products (CO-OPS)[29] provides data for tide gauge stations including tidal datum levels, tide predictions, comparison of predicted versus actual tide levels, currents and other meteorological and oceanographic parameters of interest.

The Caribbean Coastal Ocean Observing System (CARICOOS)[30], integrates coastal ocean data and forecasts from satellites, ocean instruments, and numerical models, to provide data on historical, current, and forecasted ocean conditions. Tide and current observations and forecasts around Puerto Rico can be found online.[31]

The USACE used its ADVanced CIRCulation (ADCIRC) model to simulate tidal conditions and associated circulation in various ocean basins. Its Western North Atlantic, Caribbean and Gulf of Mexico databases cover all waters west of the 60^0 West Meridian and east of the North American continent. They include the M2, S2, N2, K2, O1, K1, Q1, M4, M6 and STEADY tidal constituents. All phases are relative to the Greenwich Meridian. Included in each archive is a grid file and FORTRAN source code that extracts all constituents at user specified locations. The databased are made available free of charge for use as boundary conditions for local area circulation model.

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[26] Applied Technology Council, Wind Speed by Location website, URL: http://windspeed.atcouncil.org/

[27] National Oceanic and Atmospheric Administration (NOAA), Historical Hurricane Tracks, URL: https://coast.noaa.gov/hurricanes/

[28] NOAA National Centers for Environmental Information, URL: https://www.ncdc.noaa.gov/

[29] NOAA, NOAA Tides and Currents website, Center for Operational Oceanographic Products and Services, URL: https://tidesandcurrents.noaa.gov/

[30] Caribbean Coastal Ocean Observing System (CARICOOS), URL: https://www.caricoos.org/

[31] CARICOOS Tides and Currents Observations and Forecasts, URL: https://www.caricoos.org/#!?detail=SelectCurrents

Surge and Waves

The Federal Emergency Management Agency (FEMA) flood mapping program[32] provides base flood (100 year mean recurrence interval or 1% annual chance of occurrence) still water elevations and flood elevations that include storm wave components. In addition, the associated Flood Studies provide flood level for more frequent flooding conditions

The USACE has completed long-term wave hindcast studies for the US. The data from these studies are available from the USACE's Wave Information Studies (WIS) website[33]. The site includes data from seven wave hindcast stations that surround Puerto Rico. Data includes time series of wave heights and periods, and wind speeds and directions. Also included are analyses of the data include wave statistics, and wind and wave roses.

NOAA's National Data Buoy Center[34] provides datasets of recent and historical measurements from its fleet of offshore buoys that monitor oceanographic and meteorological parameters.

Wave observations and wave forecasts can also be

S***ea Level Rise-*** The US Environmental Protection Agency (US EPA) has a Sea Level Rise site[35] that provides data and guidance on a range of sea level rise topics. It provides links to information as to current and future sea level rise, related impacts, as well as links to tools such as NOAA's sea level rise inundation viewer, the USACE sea level change curve calculator and the US Geological Survey's Sea-Level Rise Modeling Handbook.

Other Oceanographic Parameters – The Group on Earth Observations (GEO), a consortium of over 100 nations with an intergovernmental protocol related to Earth observation, commissioned a global map of Ecological Marine Units (EMUs) to support the wise use of ocean resources and the preservation of environmental resilience. The strength of EMUs is that they differ from existing maps of marine ecoregions or biogeographic realms by being globally comprehensive, quantitatively data driven, and truly 3D. Rigorous statistical clustering produced 37 physically and chemically distinct volumetric regions where the chemical properties are most likely to drive ecosystem responses. Individuals can gauge indicators of positive or negative trends and use data to make informed decisions that preserve marine environments. ESRI supports the web-based GIS EMU mapping tool.

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[32] Federal Emergency Management Agency (FEMA), Flood Mapping Products, URL: https://www.fema.gov/flood-mapping-products

[33] US Army Corps of Engineers, Wave Information Studies, URL: http://wis.usace.army.mil/

[34] NOAA, National Data Buoy Center, URL: http://www.ndbc.noaa.gov/

[35] US Environmental Protection Agency (US EPA), Sea Level Rise, URL: https://www.epa.gov/cre/sea-level-rise