

Natural and Nature-Based Solutions Job Aid for Sandy Shorelines/Dune Restoration/Enhancement in Puerto Rico

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FEMA

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Quality information

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1. Introduction and Background

As climate change continues to pose significant challenges in coastal areas, the need for sustainable and resilient shoreline management strategies is becoming increasingly critical.

This document is a job aid that aims to provide Federal Emergency Management Agency (FEMA) personnel and stakeholders with field guidance specific to Puerto Rico on using Natural and Nature-Based Solutions (NNBS) to stabilize shorelines through the protection, enhancement or restoration, and creation of sand dunes in alignment with FEMA's strategic goals for climate resilience.²

In alignment with NNBS, “a Nature-Based Solution (NBS) is an action that incorporates natural features and processes to protect, conserve, restore, sustainably use and manage natural or modified ecosystems to address socio-environmental challenges while providing measurable co-benefits to and benefit both people and nature.”¹

1.1. Objectives of This Job Aid

The objectives of this job aid are to:

- Increase the understanding and awareness of NNBS and the role of NNBS in shoreline stabilization.
- Provide technical guidance on the implementation of NNBS for shoreline protection in Puerto Rico.
- Illustrate the benefits and effectiveness of NNBS in mitigating coastal erosion and enhancing coastal resilience.
- Facilitate informed decision-making in selecting NNBS in various coastal contexts that may qualify for FEMA mitigation-related funding.

1.2. Background on Coastal Erosion

A beach profile is the cumulative result of various natural forces that vary seasonally. The direction and magnitude of littoral or longshore currents, tides, waves, wind, sediment characteristics and vegetation contribute to the beach profile. Imbalances in these variables can cause shorelines to erode inland or accrete seaward. During extreme events such as tropical storms and hurricanes, elevated wave heights and surge can cause the shoreline and beach ecosystems to retreat farther inland. Over time, shorelines can accrete seaward if sufficient sediment deposition is present and there are no artificial structures that limit or obstruct the process. A typical beach profile is shown in Figure 0-1 for reference.

¹ U.S. Department of the Interior, “Nature-based Solutions” (n.d.), <https://www.doi.gov/ppa/integrative/nature-based-solutions>.

² FEMA, 2022–2026 FEMA Strategic Plan: Building the FEMA our Nation Needs and Deserves (n.d.), https://www.fema.gov/sites/default/files/documents/fema_2022-2026-strategic-plan.pdf.

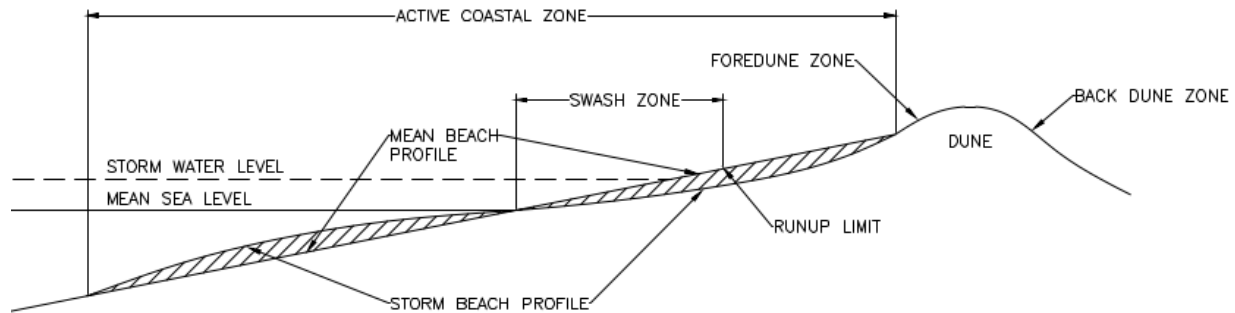


Figure 0-1: Typical beach profile

Coastal erosion can result in the loss of land, infrastructure, and habitat along the coast and threaten communities and ecosystems. Erosion can be exacerbated by factors such as sea level rise, increased storm intensity, and construction and development that interrupt or alter the natural forces that contribute to a healthy, dynamic shoreline.

1.3. The Role of Gray Infrastructure

Traditional gray shoreline infrastructure, while effective in some contexts, can lead to adverse environmental, economic and social impacts, potentially making them unsustainable in the long term. For example, bulkheads, revetments and seawalls may unintentionally accelerate erosion rates at the base of a structure, or adjacent to it, where waves are reflected, leading to increased water depth at the structure toe and reduced sediment deposition over time. Other gray infrastructure, such as groins and jetties, trap sediment on the updrift side of longshore currents and encourage accretion. However, the contrary happens on the downdrift side where sediment is not deposited due to the interruption of longshore transport by the structure.

Gray shoreline infrastructure such as shown in the bottom photo of Figure 0-2 can have residual impacts in which temporary protection in one area leads to increased erosion in adjacent, unprotected areas. Such residual impacts can lead to the degradation of the shoreline; loss of value for recreation, tourism, and wildlife (e.g., nesting sea turtles); permanent obstruction of shoreline access; and loss of visual appeal.



Figure 0-2: Top: former sandy beach at Punta Las Marias in San Juan, Puerto Rico. Bottom: same site after the construction of a steel sheet pile bulkhead with a concrete cap to manage swells and coastal flooding. The bulkhead exacerbated to the loss of sand, further coastal erosion at the toe of the structure, reduced public access, and the loss of recreational and ecological values once associated with this beach area (N. Pérez, used with permission).

1.4. NNBS in Shoreline Stabilization

NNBS consists of strategies that use natural processes and ecosystems to mitigate coastal erosion, enhance shoreline resilience, and offer a holistic approach to shoreline management. Strategies such as dune restoration use nature to absorb wave energy, stabilize sediments and reduce the impact of storm surges while maintaining or enhancing natural assets that provide the foundation for beach-related tourism and recreational activities. NNBS strategies also often provide multiple co-

benefits such as habitat creation, improved water quality, and recreational tourism opportunities. Using NNBS to stabilize shorelines not only aligns with FEMA's climate resilience goals but also supports broader ecological and community resilience. Figure 0-3 depicts sandy shoreline NNBS examples, some of which are covered in more detail in this job aid.

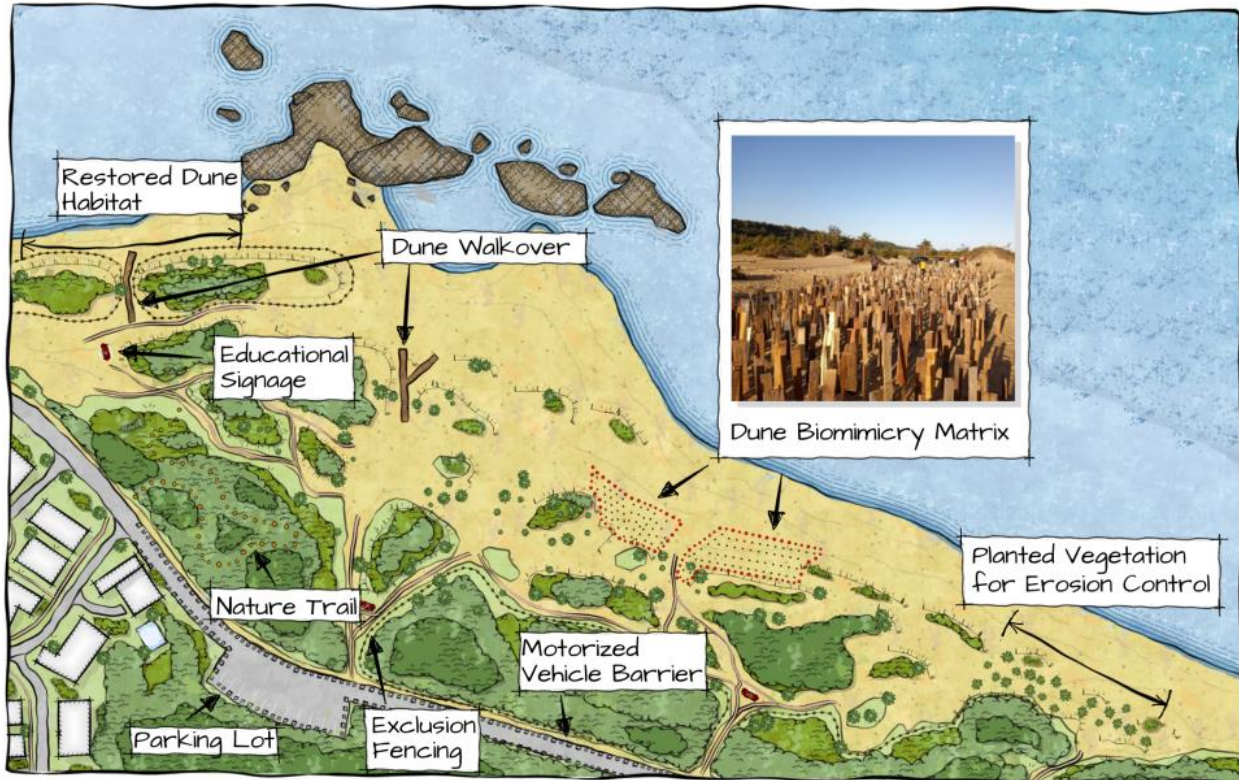


Figure 0-3: Examples of sandy shoreline NNBS

2. Sandy Shoreline Geography

Across the shorelines of Puerto Rico, coral reefs, seagrass beds, mangrove forests, rocky outcrops and sand dunes are important habitats known for their ability to buffer waves and currents that are associated with shoreline retreat and flooding. Healthy ecosystems support adjacent habitats, which together provide more protection than an individual ecosystem or habitat under both non-storm and storm conditions. Thus, it is extremely important to consider the interrelationships between ecosystems and how to maximize their combined effects when evaluating NNBS for specific shorelines.³

For simplification, this job aid focuses on the protection, enhancement/restoration and/or creation of sand dunes as a key NNBS to promote shoreline stabilization.

³ G. Guannel, K. Arkema, P. Ruggiero, and G. Verutes, "The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience" (PLoS ONE 11(7), 2016), <https://doi.org/10.1371/journal.pone.0158094>.

2.1. Sandy Beaches

Puerto Rico's beaches are diverse, ranging from expansive sandy stretches to smaller pocket beaches separated by rocky outcrops. Most beaches include a mix of quartz, feldspar sand, shell fragments and coral rubble. Less common are beaches that include sand-limited shorelines consisting of volcanic bedrock or alluvial deposits from nearby rivers.

The northern coast of Puerto Rico features dynamic sandy beaches that are subject to high wave energy, which contributes to a more aggressive erosion pattern than elsewhere on the island. In contrast, the southern coast experiences less wave action, due partially to a wider shelf and shallower water depths approaching the shoreline. Puerto Rico's southern coast is also characterized by smaller pocket beaches that are intertwined with fringing mangroves and tidal flats.

Beaches across Puerto Rico are on the frontline of coastal erosion caused by human activities. For example, tourism, residential, transportation and utility projects frequently magnify natural erosion processes, and regular foot traffic and construction near sandy shorelines disrupt the natural sediment balance, leading to more rapid erosion rates.

Climate change-driven sea level rise and storm intensity will continue to amplify coastal erosion, storm effects and coastal flooding, posing substantial risks to habitats, infrastructure and community livelihoods. The loss of beach area can lead to a cascade of negative ecological consequences, including the loss of nesting grounds for sea turtles and weakening of natural barriers that protect the inland areas from storm surges and coastal flooding. On the contrary, wider beaches with dunes and vegetation are more stable and less prone to sediment loss over time and provide various ecological benefits to the immediate and surrounding ecosystems.

2.2. Dunes

Dunes are a significant feature along the northern shoreline of Puerto Rico where natural conditions favor their formation. These dunes exhibit a range of formations, from loosely structured sand berms or mounds to more consolidated sand or eolianite structures. Loosely structured dunes are typically found in areas with higher sand mobility, where wind and wave actions continuously shape the dune landscapes. A typical dune profile is shown in Figure O-4.

The varying stability of the dunes in Puerto Rico presents distinct challenges. Loosely structured and low elevation dunes are particularly susceptible to further erosion, which can not only lead to the loss of these natural barriers but also expose inland areas to increased coastal hazards. Low elevation dunes, especially those lacking vegetation, offer limited protection and are easily reshaped or removed by storm surge or high-energy wave action. Erosion of these dunes can result in increased vulnerability of the shoreline, loss of habitats for dune-dependent species, and potential negative impacts on nearby beach infrastructure.

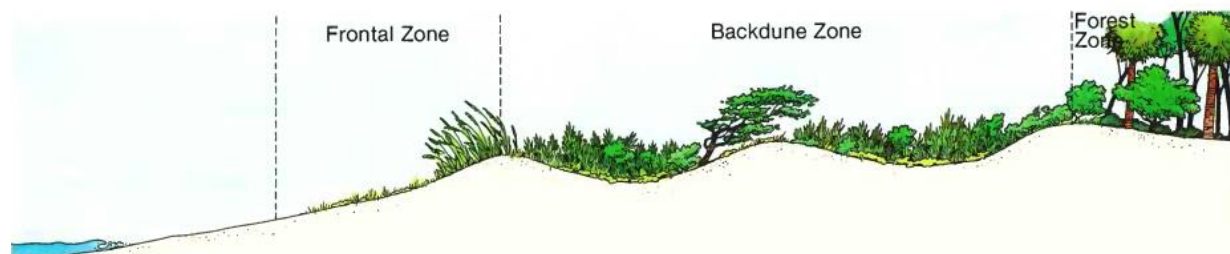


Figure 0-4: Typical dune profile (Craig, 1984)

3. NNBS Conceptual Designs and Methodologies

This section discusses two NNBS strategies for improving shoreline stabilization that are suitable for the typical sandy shoreline environments in Puerto Rico. Both strategies are intended to promote a healthier and more stable beach ecosystem and are achieved by implementing projects consisting of NNBS solutions.

The strategies are as follows:

- Improving public access to the coast to protect existing sand dunes by developing formal beach accessways such as improved roadways, parking areas, boardwalks, and dune walkovers; see Section 3.1.
- Restoring and creating dunes; see Section 3.2.

Section 3.3 discusses the plant species that could be used for either strategy, time of planting and plant availability.

Both strategies should include signage to reinforce or raise awareness among beachgoers about the importance of conserving the area's ecosystems and any rules or best practices that need to be followed to maintain the area's functions and values.

The description of each strategy in Sections 3.1 and 3.2 includes solutions, applicable project sites, construction, typical section drawings, monitoring and estimated costs. Itemized costs (cost of equipment, material and labor needed for each project type) are available for download through FEMA's website⁴ and can be used to estimate the total project cost as a function of the project's total extent or area.

The proposed projects discussed in this job aid could be developed on public domain land that corresponds to the maritime terrestrial zone (zona marítimo-terrestre or ZMT) including the two adjoining easements that comprise a total width of 65.6 feet (20 meters). See Section 3.5 for more information about ZMT. Determining the extent of and assessing this land is therefore critical. Also critical is to recognize the need for open, undeveloped space for any of the proposed projects. Some

⁴ [URL with itemized costs of NNBS solutions for Puerto Rico shoreline]

projects may need to use a portion of adjoining private lands to make the projects more effective in protecting nearby public and private structures from coastal erosion and storm surge flooding.

None of the projects discussed in this job aid should be developed in the swash zone, the area that is frequently washed by tides and where waves run up the beach during normal weather conditions (see Figure O-1). The landward edge of the swash zone or runup limit varies throughout the year in response to the tides and swells. To account for the variability, the existing limit of the vegetation facing the ocean at a given site can be used as a reference point to determine the landward boundary of the swash zone. Once identified, the line of vegetation can be used to establish the boundary of the project's ocean-most extent. In shorelines without vegetation, the approximate landward limit of the swash zone can be determined by identifying the area that is reached by wave runup from swells associated with nor'easters or cold fronts that reach Puerto Rico during the winter.

The sandy beaches in the northwestern, northern and northeastern coasts of the island usually narrow or retreat the most in January and February. The same may happen on the southern coast but during late summer and early fall (August to September) in response to swells associated with tropical waves moving across the Caribbean Sea. In any case, delineating the swash zone at a given beach before initiating any of the projects discussed in this job aid is recommended. The delineation should be performed by a professional (e.g., registered professional land surveyor, oceanographer, geomorphologist).

Any structures built to guide beach access, including structures intended to enhance or create a sand dune, have a better chance of becoming well established if they avoid the swash zone and, with it, any frequent surf-related impacts. Avoiding the swash zone also allows any vegetation to be planted and used to help sand dunes become well established and sturdy and thus resilient to the effects of extraordinary swell and storm surge flood events.

Project planning should include determining the potential presence of threatened or endangered listed species in sand dunes or along a shoreline where work will take place including species that may use the area for reproduction. The construction timeline of a project should include a consideration of the nesting season of coastal species such as sea turtles and migratory birds that lay their eggs behind the high tide water mark (e.g., leatherback sea turtles, plovers, pipers) or higher up in the dune where there may be woody vegetation (e.g., hawksbill sea turtles). A qualified professional such as a biologist or ecologist should be hired to survey and monitor the construction site and its immediate vicinity during early morning hours before construction work starts to identify the presence of nests and avoid potential impacts on these species.

3.1. Improved Public Access to the Coast

This section details the projects that address public access through NNBS.

3.1.1. DESCRIPTION OF SOLUTIONS AND OBJECTIVES

Establishing clear pathways to facilitate beach access is key to preventing foot traffic and vehicles from damaging or destroying vegetation and creating depressions or blow-outs across sand dunes.

Boardwalks and dune walkovers that traverse dune systems and sensitive parts of the beach environment allow direct public access to shorelines, which reduces or may eliminate foot traffic on or between sections of dunes (Figure 0-5). Preventing foot traffic from traversing dunes and other sensitive ecosystems prevents native vegetation from being trampled, thus enhancing its capacity to thrive and expand. Simple and low-cost access solutions are key to reducing erosion and increasing the resiliency of beach and dune ecosystems.



Figure 0-5: Boardwalk constructed by Protectores de Cuencas, Inc. (a nongovernmental agency) at Playa Tamarindo in the Guánica State Forest Nature Reserve (Rios, 2021, used with permission)

Prohibiting vehicular traffic in natural shoreline areas is similarly essential for ecosystem health. In addition to foot traffic, vehicular traffic through dune systems or onto beaches severely degrades vegetation, impacts natural water flows and increases erosion. Carefully constructed or improved roads and clearly designated parking infrastructure that facilitate public access to shorelines can have significant positive impacts on the ecosystem. Using bollards, fencing, or boulders are simple yet effective ways to confine vehicular traffic to the roadway. Additionally, a well-built and maintained gravel road can provide access and encourage the public to use designated parking that is ideally paired with nearby and direct access to the shoreline. Properly constructed areas can manage surface runoff to protect the integrity of access infrastructure while enhancing water quality and preventing erosion caused by runoff flows. Quality amenities and direct access will encourage the public to take the path of least resistance to the shoreline and can be engineered to protect and promote shoreline resiliency.

Improved beach access can provide social and economic benefits to local communities. The benefits can be quantified to align with FEMA grant requirements including benefit-cost analyses while also providing environmental justice and equity measures.

3.1.2. SUITABLE ENVIRONMENTS FOR SUCCESSFUL IMPLEMENTATION

The access improvements discussed here are ideal for both urban and rural areas, but the most suitable candidates for improvement are beaches, dunes and shorelines that have been degraded by human activities. The need for these improvements can be seen in remote locations where limited access infrastructure results in unregulated vehicle and foot traffic over environmentally sensitive areas. Urban areas may require access improvements where space is limited (e.g., for parking) or where unrestricted access that bypasses urban infrastructure is through adjacent undeveloped land.

3.1.3. CONSTRUCTION MATERIALS AND EQUIPMENT

Gravel base and other surface material are generally the primary construction aggregates used in roadway and parking improvement projects. It is imperative for the proper compaction, durability and life expectancy of the infrastructure that materials are both well graded and properly compacted. Motor graders and vibratory rolling compactors are normally used to shape, grade and compact road material. Excavators and dump trucks are commonly used to excavate in situ material if needed, depending on site conditions. Geotextile fabric is placed beneath the base course and consists of heat bond or woven fabric. Hydroseeding equipment typically used for turf reestablishment over excavated grade and areas disturbed by heavy equipment movement consists of pumps, slurry tanks, hoses and a spraying nozzle. Sod can be used for turf re-establishment and requires less equipment but typically is not as economical for large-scale projects.

Dune walkover structures are commonly built with readily available lumber and hardware from lumber suppliers or home improvement stores. Using pressure-treated lumber for outdoor wooden structures is necessary to protect the structures from rot, insects and weather. Composite building materials blended from wood particles, plastics and other additives are also available and are commonly used for deck boards. Composite building materials offer more weather resistance and greater longevity than lumber but at an increased price. Dune walkover structures can be constructed by skilled laborers with common hand tools such as drills and impact drivers. Handheld gasoline augers and manual post-hole diggers are ideal for setting dune walkover piles. Large equipment such as tractors and skid steer auger attachments are not recommended due to the equipment's impact on the dune system.

3.1.4. CONSTRUCTABILITY

Boardwalks, walkways and stairways across dunes must be properly oriented to avoid creating damaging wind and wave tunnels. The recommended approach is constructing the last 15- to 20-foot segment of the structure at an angle away from the dominant wind and wave direction as shown in Figure O-6, Example B. The alignment change can be constructed in a more sheltered area farther inland to reduce the length of the walkway and with it, the resulting footprint and associated impact on the cost of vegetation and construction.

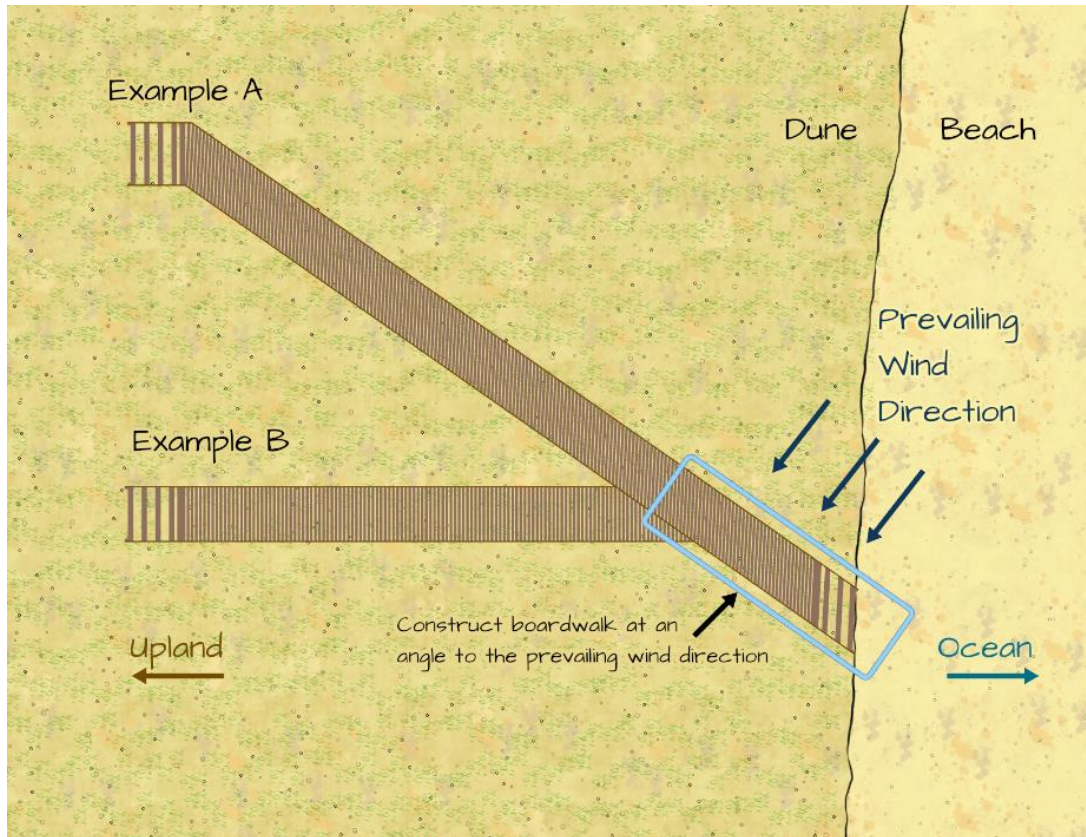


Figure 0-6: Boardwalk orientation

Figure 0-7 through Figure 0-11 represent typical sections of solutions for access improvements discussed previously (dune walkovers and parking and roadway infrastructure). The figures are for informational purposes only; individual project design conditions may vary and structures and solutions must be designed on a per project basis to serve the project site effectively and safely.

Dune Walkover

A typical 8-foot-long dune walkover section is detailed in Figure 0-7 and Figure 0-8. Support posts should be driven a minimum of 3 feet into the existing grade for proper support using a handheld gasoline auger. Additionally, the structure should be 3 feet above the existing grade to allow proper sunlight penetration to the vegetation below, allow the sand to move, and avoid potential impacts to the structure from wave runup during extreme storm surge or swell events. Entry and exit sections can consist of ramps or stairs depending on the elevation and distance available for tying into the dune walkover.

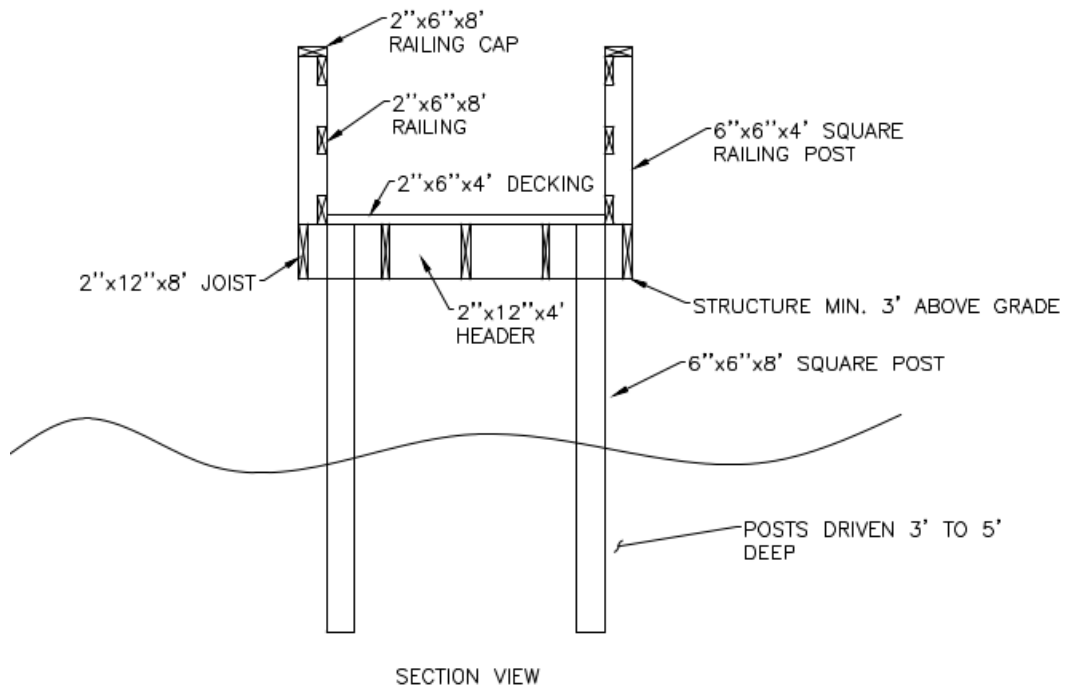


Figure 0-7: Typical dune walkover section view

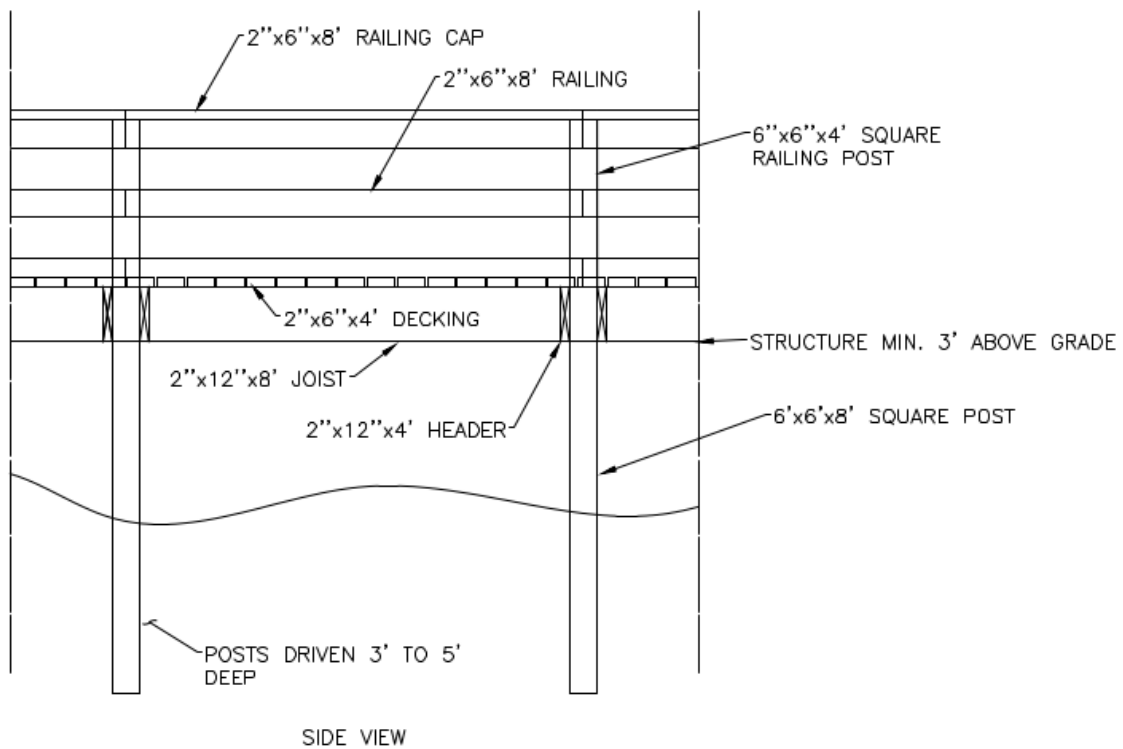


Figure 0-8: Typical dune walkover side view

Parking and Roadway Infrastructure

Typical parking and roadway infrastructure to access a shoreline is shown in Figure 0-9 and Figure 0-10. The parking and roadway sections consist of 6-inch and 12-inch compacted, well-graded surface and base material, respectively. Parking areas and roadways are confined by bollards spaced every 6 feet to restrict vehicular access and include side drainage swales sized for proper conveyance of runoff to prevent erosion and improve water quality. The roadway cross slope is 24:1 from the crown to the edge of pavement, and the parking area cross slope can vary depending on the site characteristics and dimensions of the parking area. Properly grading the parking area to drain runoff toward each drainage swale is recommended and should not be steeper than the 24:1 roadway cross slope. Implementation of other NNBS drainage features, such as rain gardens, can further mitigate poor runoff water quality and manage excess runoff flows. While typical dimensions are given for reference, local roadway design manuals, standards and criteria should be used to verify conformance.

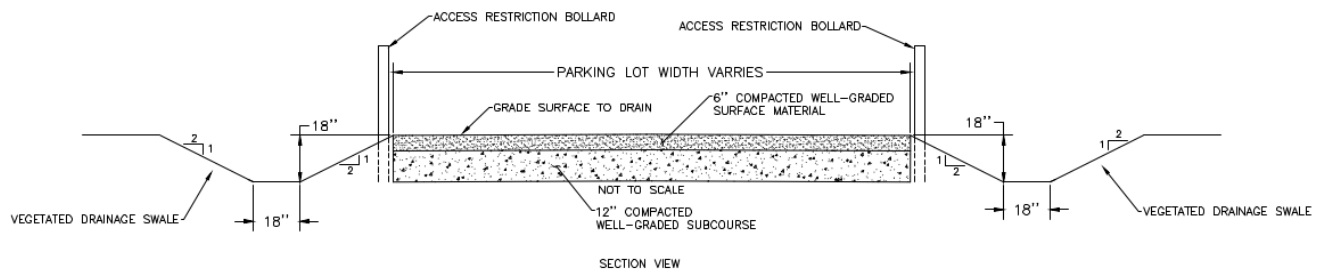


Figure 0-9: Typical access parking section

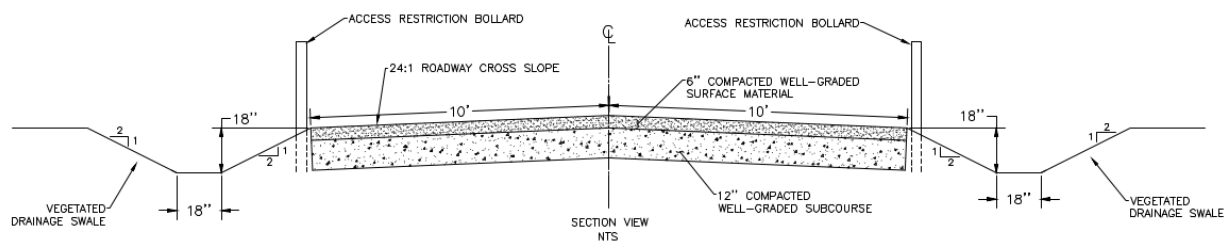


Figure 0-10: Typical two-lane access road section

Vegetated Drainage Swale Natural Check Dam. Expanding on Figure 0-9 and Figure 0-10, a typical view of the vegetated swale, also known as a natural check dam, is shown in Figure 0-11. Within the grass-lined banks of the drainage swales, a dense segment of deeper-rooted native grasses or shrubbery should be planted with a thin layer of 6-inch riprap surrounding the vegetation. The riprap toe of the check dam will aid in preventing erosion around the base of the plants in extreme events. Check dam spacing should be determined by the grade along the swale where each successive

check dam’s effective water retention height (the height of the water pooling in front of the check dam during a storm) aligns with the bottom of swale (flowline) elevation of the upstream check dam.

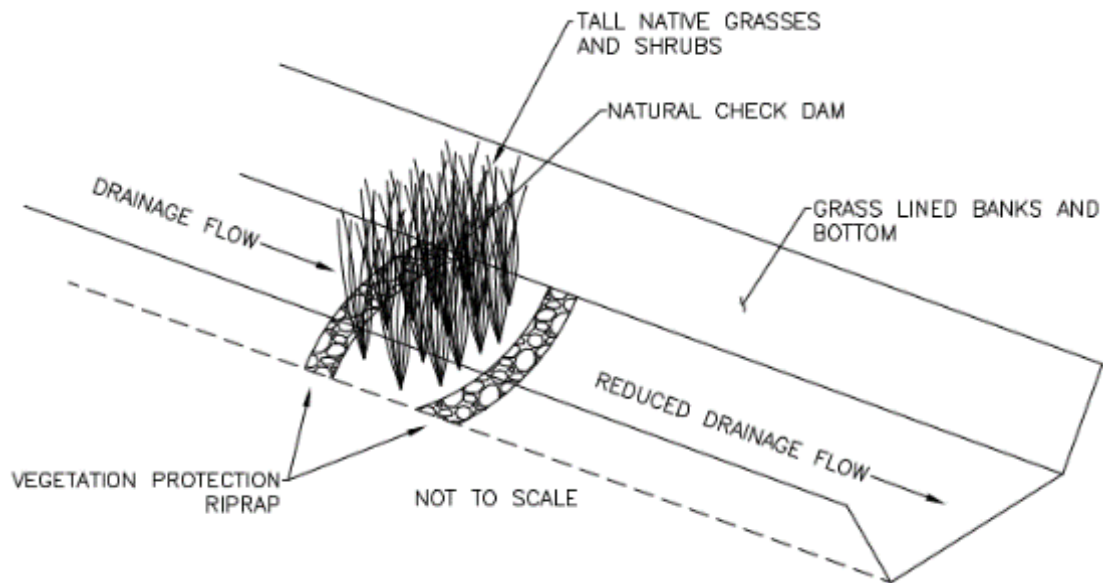


Figure 0-11: Typical natural drainage check dam

3.1.5. MONITORING AND ADAPTIVE MANAGEMENT

Dune growth and vegetation survival beneath dune walkover structures need to be monitored as dune elevations shift and change. The ground beneath the dune walkover may accumulate sand or erode over time due to wind-transported sand or elevated wave and flooding events. Monitoring change over time is important for the survival of vegetation beneath the structure and structural stability of the piles supporting the dune walkover. Vegetation and sunlight coverage directly under dune walkover structures should also be monitored to ensure that the amount of sunlight below the structure is sufficient. Deck spacing can be increased to allow more sunlight through the structure to the vegetation below but not so far as to become a tripping or other hazard for the public.

The dune walkover structure should be inspected visually on a regular basis for structural issues such as broken boards, shifted piles and corroded bolts and other connection hardware. Any broken or damaged members or hardware should be replaced immediately. To protect public safety, traffic cones or tape may be used to cordon off access to a dune walkover until it is repaired.

Road and parking infrastructure needs to be monitored for potholes, road erosion, degraded drainage infrastructure and damaged vehicle access restriction structures such as bollards, fencing and boulders. According to the Federal Highway Administration, the estimated cost of annual 6-year maintenance cycles for gravel roadways was approximately \$18,000 per mile in 2015.⁵ Accounting for inflation, the current (2024) estimated 6-year maintenance cost is approximately \$23,750 per

⁵ FHWA (Federal Highway Administration), Gravel Roads Construction & Maintenance Guide (2015), <https://www.fhwa.dot.gov/construction/pubs/ots15002.pdf>.

mile.⁶ Frequent monitoring and timely maintenance or repair of identified issues can aid in preventing worsening impacts and reduce overall costs. Road and parking infrastructure should be inspected after significant weather events to identify any repairs or maintenance needs.

3.1.6. ESTIMATED COSTS

Costs for the access solutions were compiled from materials, equipment and labor costs that represent constructing the typical sections discussed in Section 3.1. The costs are listed in **Error! Not a valid bookmark self-reference.** Unit costs used to develop the estimated costs are intended to be representative of costs in Puerto Rico (2024 U.S. dollars).

Table 0-1: Shoreline Access Estimated First-Time Construction Costs (2024 U.S. Dollars)

Typical Section	Estimated Unit Construction Cost
Dune walkover	\$80 to \$98 / LF \$750 gasoline auger (one-time fixed price)
Road improvements	\$712,000 to \$871,000 / mile
Parking improvements	\$56 to \$69 / SY

LF – linear foot
SY – square yard

3.2. Dune Restoration and Creation

This section details the projects that address dune restoration and creation through NNBS.

3.2.1. DESCRIPTION OF SOLUTIONS AND OBJECTIVES

Restoring dunes, which includes protecting, rebuilding, and improving them, and creating dunes are important methods of increasing the resiliency and long-term stabilization of sandy shoreline ecosystems. Restoring degraded and eroded dunes can include intercepting sand from wind-born sediment or transporting sand to the shoreline. Sand fencing has been proven to reduce wind to a speed at which sediment falls out of suspension, accumulates, and eventually establishes dunes around the fence.⁷

Sand fencing and other sand accumulation techniques have led to the development of biomimicry or sand matrices as an NNBS solution in which boards are spaced evenly center to center along the project footprint. The height of the boards can vary to shape the accumulation of trapped sediment. In addition to constructing sand matrices, it is important to plant vegetation to further reduce erosion and capture additional sediment. Sand matrix infrastructure that captures sand also helps protect

⁶ U.S. Bureau of Labor Statistics, “CPI Inflation Calculator” (n.d.), https://www.bls.gov/data/inflation_calculator.htm.

⁷ L. Bailiang and D.J. Sherman, “Aerodynamics and Morphodynamics of Sand Fences: A Review” (Aeolian Research, 2015), <https://www.sciencedirect.com/science/article/abs/pii/S1875963714001025>.

new vegetation. The Vida Marina Center for Conservation and Ecological Restoration, University of Puerto Rico at Aguadilla, project discussed in Section 4.1 demonstrates the feasibility of implementing sand matrices and that it can be effective within a short time frame.

In areas that need immediate restoration, dune nourishment may be necessary where sand can be transported to the shoreline and shaped using equipment. Diverse coastal and dune vegetation is needed to increase the likelihood that the sediment on new or reconstructed dunes will be retained. Including a mix of species for frontal and back dune zone plants, such as grasses, other herbaceous plants, vines, shrubs, and trees, will help retain sediment across a range of environmental events. Section 3.2.3 discusses the species and planting zones that are applicable to Puerto Rico.

3.2.2. SUITABLE ENVIRONMENTS FOR DUNE RESTORATION AND CREATION

Dune restoration is ideal for shorelines with wave and flooding exposure. Locations with reduced wave energy from offshore reefs, limited fetch distance, or protection from open ocean swells from surrounding geography are preferable for smaller scale or lower budget projects. These environments tend to require lower dune elevations, which reduce the cost of materials and shorten the construction schedule. Sand fencing can be applicable in these locations if sediment and corresponding winds to transport sand are both sufficient. Constructing dunes using new material is recommended for sites where sand fencing may not be as effective.

Sand matrices are ideal for projects with lower budgets or when restoring dunes using imported and shaped fill is not feasible. Simple materials and a straightforward construction process make this solution easy to implement and adaptable to various site conditions. Sand matrices are also suitable for environments with larger dune systems. Due to higher natural dune heights in some areas of Puerto Rico, it may not be economical to construct or rebuild 12- to 14-foot-tall dunes by trucking in material. Using sand fencing or matrices can be a cost-effective solution that allows gradual sand accumulation and dune creation. Wooden sand matrix boards can be readjusted as dune development is monitored to ensure that growth progresses. For all sand matrix projects, it is important to select a site with sandy beaches that span the shoreline and sufficient wind speeds that will allow the sand matrix to be effective in capturing sediment from wind-borne transport. If sediment is scarce and/or wind speeds are consistently low at the site, the sand matrix solution may not be effective for restoration.

3.2.3. CONSTRUCTION MATERIALS AND EQUIPMENT

Dune projects constructed with new material require appropriate sediment that is similar to the existing sediment in grain size, angularity, color, and composition and that is free of contaminants. Construction methods typically use skid steers and dozers to move materials after they are brought to the project site via dump truck.

Alternative materials can be used in place of, or preferably blended with, in situ sand, especially sand composed mostly of quartz. For example, crushed glass or recycled glass cullet can be used alone or in combination with boulders to reinforce the core when creating an artificial sand dune. Research indicates that recycled glass cullet is a viable and compatible fill material that can be safely used for

beach nourishment.⁸ Geotechnical analyses of glass cullet show that grain size, color, and angularity are similar to native beach sand, and biological and abiotic testing both demonstrate that recycled glass cullet is a biologically benign material that will not negatively impact microfauna or macrofauna or interfere with sea turtle embryo development.⁹ Costs related to the collection (e.g., glass bottles) and processing of crushed glass, including the identification of readily available inventories, need to be assessed to determine the feasibility of using this material for sand dune restoration or creation in Puerto Rico.

Sand matrices can be constructed from wide, thin wooden boards. The boards can be sourced from lumber suppliers, home improvement stores, or reused lumber from pallets or other recycled sources. Many logistics and shipping companies give used pallets away or for a low cost, so pallets can be an attractive option for small-scale or low-budget projects. As with dune walkovers, treated wood is preferable for its durability in outdoor/marine environments. However, not all pallet wood is treated, and if not, it can be treated with various chemicals or processes. Therefore, the longevity of the material in a wet environment may differ. The effective use of pallet wood in sand matrices has been demonstrated in Puerto Rico and can be a key component of reducing the construction cost of sand matrix projects.

3.2.4. CONSTRUCTABILITY

Sand matrices are much simpler and quicker to construct than dune restoration projects involving imported fill. Imported fill dune restoration typically involves more material and logistical coordination, material testing, surveying, and up-front engineering design. Sand matrices do not require fill material testing, pre- and post-construction surveys or mobilizing to and demobilizing heavy equipment from the site. Boards for sand matrices can be readily installed using a manual gasoline auger. The board should be oriented, so the flat side faces the prevailing wind for proper accretion efficiency.

Figure 0-12 through Figure 0-14 show typical sections of the solutions for dune restoration and creation that are discussed previously (dune creation using imported fill and wooden sand matrices). The figures are for informational purposes only; individual project design conditions may vary, and structures and solutions must be designed on a per project basis to serve the project site effectively and safely.

Dune Creation Using Imported Fill (Dune Nourishment)

The dune section in Figure 0-12 represents a 4-foot-tall, single-row sand dune created from imported fill with 3:1 side slopes and a 1 foot wide crest. Plants should be spaced at 18-inch center-to-center

⁸ Georgia Coastal Research Council, "Use of Pulverized Recycled Glass for Beach Nourishment: A Review" (2018), https://www.gcrc.uga.edu/wp-content/uploads/2019/10/Review-Use-of-Pulverized-Recycled-Glass-for-Beach-Nourishment_v1.pdf.

⁹ Georgia Coastal Research Council, "Use of Pulverized Recycled Glass for Beach Nourishment: A Review."

intervals along the slope areas for sufficient sediment retention unless otherwise specified by the supplier.

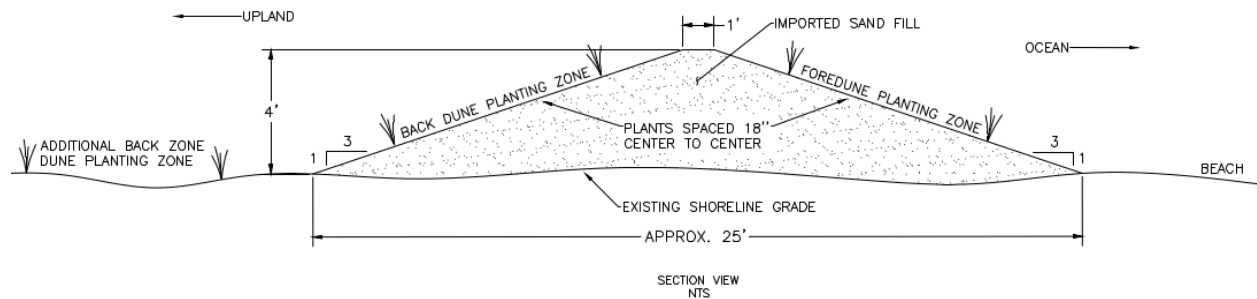


Figure 0-12: Typical section of dune restoration

Sand Matrices

Figure 0-13 and Figure 0-14 depict a typical sand matrix layout and section, respectively. Boards are driven to a minimum depth of 1.5 feet below the existing grade and are spaced approximately 1 foot apart on center. Top elevations of the boards can be adjusted as needed to optimize the accretion topography to a desired profile. Both foredune and back dune vegetation species can be planted between board spacings within the sand matrix, while back dune vegetation species may also be planted behind the matrix structure to encourage sand retention and provide opportunities for natural voluntary regrowth of the vegetation once sand accumulates.



Figure 0-13: Sand matrix typical layout (R.J. Mayer, used with permission)

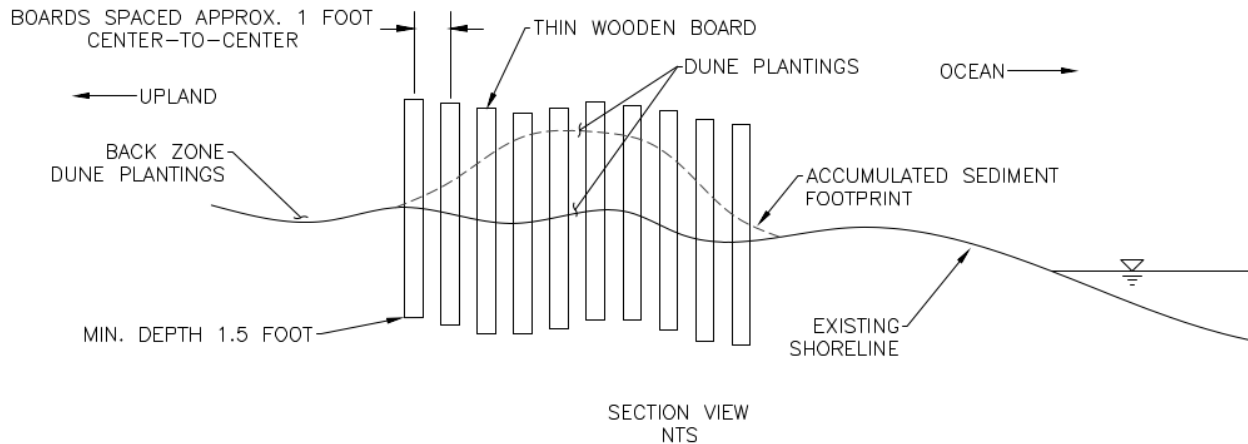


Figure 0-14: Typical section of sand matrix

3.2.5. MONITORING AND ADAPTIVE MANAGEMENT

Sand dune construction projects need to be monitored after implementation to document the growth of vegetation on the dune, any accretion or erosion at the site, and the project’s effectiveness as a shoreline protection system. Degraded areas can be further planted to reduce erosion, or sand fencing/matrices can be installed to improve sediment capture to combat the erosion if appropriate. If foot or vehicular traffic is impacting the new structure, additional fencing and signage can be added.

Restoration with sand fencing and matrices should be monitored to document annual dune accumulation and vegetation present. The data will help inform where and how effective these structures can be and what the expected timelines are to reach desired dune profiles for a site. Measuring the dune height by using the boards as a relative measuring tool for the change in dune elevation is a simple and effective way to estimate volumetric material accumulation at the site for matrices while the boards are still emergent. Finding a nearby fixed object to use as an elevation reference point may be more suitable for long-term monitoring in the absence of formal elevation surveys.

Aerial photography of the site can be an effective way to compare vegetation growth annually or seasonally and can be performed as needed by drones or use available satellite imagery data. Real time kinematic (RTK) GPS-enabled drones that have highly accurate positional and navigational awareness can be used to evaluate volumetric changes at the site as well. It is advised that a licensed operator who has experience with high precision ortho-mosaic photography and digital surface modeling be used for these applications. Drone photography or other monitoring events should be completed during the same season/time frame from year-to-year to provide the best basis for comparison.

3.2.6. ESTIMATED COST

The estimated cost of dune restoration solutions were compiled from materials, equipment and labor costs associated with constructing the typical sections discussed in Section 3.2 and are listed in Table 0-2. The estimated costs listed in Table 0-2 are intended to be representative of costs in Puerto Rico (2024 U.S. dollars). The costs do not include a one-time fixed cost of \$750 for a gasoline auger.

Table 0-2: Dune Restoration/Creation Estimated First-Time Construction Costs (2024 U.S. Dollars)

Typical Section	Estimated Unit Construction Cost
Sand dune restoration (imported and shaped fill)	\$144 to \$176 / LF
Sand matrix (new material)	\$103 to \$126 / SY
Sand matrix (reclaimed material)	\$83 to \$101 / SY

Source: Adapted from R.J. Mayer, “Ecological Restoration of Dunes in Puerto Rico – Cost Estimates” (2024)
 LF – linear foot
 SY – square yard

3.3. Plant Selection

Dune planting should consist of a diverse mix of common species that prioritizes species that are native to Puerto Rico. Combinations of grasses, vines, shrubs and trees can develop into an erosion-resilient ecosystem.

Plant species are the same for the stabilization of sand dune projects to improve public access to the coast (e.g., boardwalks) and for the restoration or creation of dunes (e.g., sand matrices). Different plant species are categorized based on their field-observed dune growth zones to provide a natural distribution of plant species for dune restoration and creation projects.

For the lower part of the front dune where pioneer and more salt-tolerant species are found, the species that could be selected include the following:

- seashore dropseed (*Sporobolus virginicus*)
- beach morningglory (*Ipomoea pes-caprae brasiliensis*)
- beachbean (*Canavalia rosea*)
- seagrape (*Coccoloba uvifera*)
- saltmeadow cordgrass (*Spartina patens*)
- portia tree (*Thespesia populnea*)

For the upper part of the front dune, the species that could be selected include the following:

- common bermudagrass (*Cynodon dactylon*)
- coin vine (*Dalbergia ecastaphyllum*)
- cocoplum (*Chrysobalanus icaco*)
- Spanish bayonet (*Yucca aloifolia*)
- samphire (*Blutaparon vermiculare*)
- bay cedar (*Suriana maritima*)
- poison cherry (*Crossopelatum rhacoma*)
- wild cinnamon (*Canella winterana*)
- button mangrove (*Conocarpus erectus*)
- torchwood (*Jacquinia arborea*)
- seaside heliotrope (*Heliotropium curassavicum*)
- buttonsage (*Lantana involucrata*)
- inkberry (*Scaevola plumieri*)
- Bay Biscayne creeping-oxeye (*Sphagneticola trilobata*)

For the back dune section, the species that could be selected include the following:

- stiffleaf eustachys (*Eustachys petraea*)
- sandbur (*Cenchrus* sp.)
- prickly pear (*Opuntia dillenii*)
- white cedar (*Tabebuia heterophylla*)
- pinguin (*Bromelia pinguin*)
- black mampoo (*Guapira fragans*)
- shortleaf fig (*Ficus citrifolia*)
- silk cotton tree (*Ceiba pentandra*)
- West Indian birch (*Bursera simaruba*)
- gregorywood (*Bucida buceras*)
- fiddlewood (*Citharexylum spinosum*)
- pigeon berry (*Bourreria succulenta*)
- black mampoo (*Guapira fragans*)
- mast wood (*Calophyllum brasiliense*)

Potted plants from nurseries can be planted quickly in appropriate dune locations using a shovel. The availability of selected plant species for dune planting may be an important limiting factor since large quantities or certain species may not be readily available for sale at local plant nurseries. Therefore, it is important to set aside existing stock or harvest and develop seeds and/or saplings from similar, nearby coastal sites and to take advantage of the existing plant gene pool that is adapted to area's conditions, so vegetation is available when needed. It is also critical to coordinate with local suppliers to understand what vegetation can be provided, its annual availability, or whether there is an extended lead time on procurement. Ensuring that plant material is available when the project is under construction is crucial to expediting the timeline and reducing costs.

The following are recommended for grasses, vines, shrubs and trees:

- Irrigate new plantings to increase the chance of their survival over the first few weeks.
- Plant during the rainy season (August through November) to lower the cost of irrigation.
- Provide mulch around the plants to help the soil retain moisture.

Some mortality is normal due to dehydration, temperature shock, wind, salt spray desiccation, predation or suffocation by climbing vines. Accounting for the losses and planning for the logistics and cost of replacing dead plants are important.

3.4. Signage

Public information signs can be a simple but important way to showcase local restoration efforts, the benefits of healthy shoreline ecosystems, the threatened or endangered species that are in the area and rules for the proper use of the area. Signs typically include graphical and written content and are printed on a wooden board or metal plate and fixed to the ground on a post.

3.5. Site Protection

Exclusionary fencing to reduce foot traffic can protect sensitive environments such as newly planted dunes, restored shorelines, and existing dunes. Simple fencing can block foot traffic in additional sensitive areas such as newly planted or restored dune areas. Small-scale wooden or wire fencing can be cost-effective and an easy-to-install solution for protecting sensitive areas.

3.6. Regulatory Considerations

Dune walkover structures and sand dune construction, restoration and creation projects need the following:

- Permits from the Puerto Rico Permits Management Office (*Oficina de Gerencia de Permisos* or OGPe)
- Compliance with zoning requirements established by the Puerto Rico Planning Board
- Endorsement by or approval from the Puerto Rico Department of Natural and Environmental Resources (DNER) and the U.S. Fish and Wildlife Service (USFWS) on plant selection and any effects the project may have on the Commonwealth of Puerto Rico and federally listed threatened or endangered species
- Determination by the DNER of whether the project site is within public domain lands or the ZMT

Obtaining the endorsement of municipal authorities is also strongly encouraged because these authorities have a vested interest in efforts that may affect or improve the daily livelihoods of adjacent communities. Local communities and environmental/conservation nongovernmental organizations (NGOs) can become important partners for project development, monitoring and maintenance activities.

The ZMT was established by the Spanish Ports Law of 1880 (*Ley de Puertos Española*) and has been applicable to Puerto Rico since 1886 (Figure 0-15). It includes all tidally influenced areas on the coast of Puerto Rico, the banks of rivers where waters are tidally influenced and areas where water reaches inland during the highest wave events (i.e., the high water mark of waves during storm events). The ZMT also includes lands that have been reclaimed from the sea by human action (e.g., sand fill) or nature’s action (e.g., natural accretion); port areas are exempted as designated by the Puerto Rico Planning Board.

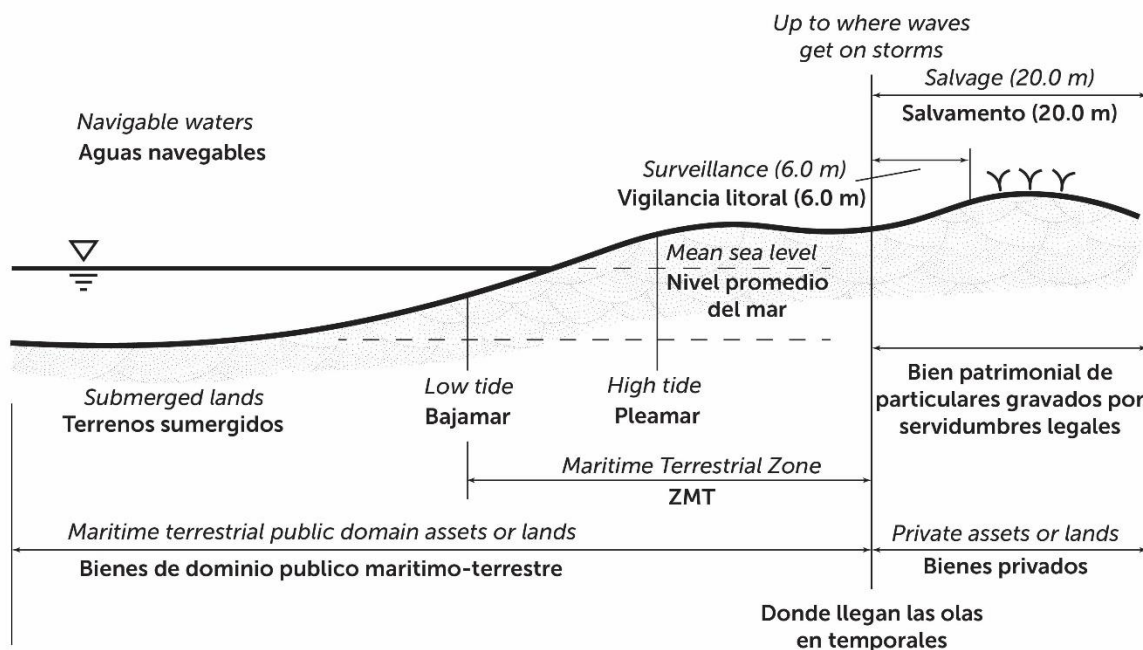


Figure 0-15: ZMT boundaries

All lands within the ZMT are public domain, meaning the lands belong to every citizen living in Puerto Rico and no one individual. The DNER does not own these lands, but the agency is in charge of or has primary authority over their management, including allowing or rejecting any proposed uses, which must be ocean-dependent activities (e.g., pier, boat ramp, port facility).

The DNER is also in charge of delimiting and certifying the inland limit of the ZMT. An area with a width of 65.5 feet (20 meters) that is parallel to the inland limit of the ZMT must remain free of permanent structures (e.g., buildings) as an easement to guarantee public access to the shore, even if the area is privately owned.

A request for a formal or official delineation of the ZMT and its easement is strongly advised to determine the exact extent of public domain lands where a project could take place before initiating any work. Additional lands or setbacks may be needed to make the project effective, depending on the extent of coastal erosion at a given site.

Based on permitting and design concerns, all construction activities should take place above the mean high-water line, outside waters of the United States, and outside wetlands to avoid impacts to adjoining ecosystems. Adjoining ecosystems may also require permitting under federal statutes such as Section 404 of the U.S. Clean Water Act of 1972 (33 U.S.C. § 1344) and Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 403). Any projects that may cause impacts to or the taking of Endangered Species Act listed species and designated critical habitat could require a Biological Opinion that is approved by the USFWS.

Permit applications should be submitted as early as possible because obtaining permits can take up to several months. Important permitting aspects are that the impacts of construction should be as minimal as possible, the structure should allow sufficient sunlight exposure for vegetation growth, and construction activities should take place within appropriate seasonal windows. Monitoring the success of completed projects can aid in future project permitting by documenting project success and the benefits the projects provide to the ecosystem.

4. Case Studies

This section highlights NNBS projects that have been successfully implemented in Puerto Rico to stabilize the shoreline using the aforementioned NNBS methods.

4.1. Strengthening the Resilience of the Coast of Puerto Rico to Extreme Weather and Climate Change through Ecological Restoration of Its Coastal Sand Dunes

The first case study, Strengthening the Resilience of the Coast of Puerto Rico to Extreme Weather and Climate Change through Ecological Restoration of its Coastal Sand Dunes, was led by the Vida Marina Center for Conservation and Ecological Restoration at the University of Puerto Rico at Aguadilla beginning in 2018.¹⁰ The type of project, cost and project partners are listed in Table 0-3.

Table 0-3: Vida Marina Sand Dune Case Study Project Type, Cost, and Partners

Project Type	Cost	Partners
Dune restoration	\$1,116,539	<ul style="list-style-type: none"> ▪ National Fish and Wildlife Foundation Coastal Resilience Grant Funding (2018 and 2019). ▪ National Oceanic and Atmospheric Administration (NOAA) funding through DNER. ▪ JetBlue for Good. ▪ U.S. Forest Service through DNER. ▪ Diversified and Special Services, Inc.

¹⁰ R.J. Mayer, "Using Novel Approaches to Create Resilient Dune Systems Following Hurricane Maria" (NOAA, Office for Coastal Management, 2024), <https://coast.noaa.gov/digitalcoast/training/puerto-rico.html>.

The main island's dunes, particularly along the northern coast in the region of Isabela and the cities of Dorado and Loiza, are vulnerable to coastal erosion due to human activities such as development. The destruction of vegetation and compaction of sand by vehicles, illegal sand extraction and heavy foot traffic have left the dunes vulnerable to erosion and displacement during storms. Hurricanes Irma and Maria in 2017, followed by Winter Storm Riley in 2018, exacerbated these issues and caused severe erosion of already damaged dunes.

Dr. Robert J. Mayer and his team at Vida Marina, which is part of the Center for Conservation and Ecological Restoration at the University of Puerto Rico at Aguadilla, pioneered an NNBS approach to address these challenges, recognizing the limitations of traditional hard structures. The team focused on ecological restoration techniques that enhance the resilience of dune systems. The restoration process involved five steps:

1. Select coastal dune sites based on vulnerability to storms and population density.
2. Use drones to capture aerial imagery for pre- and post-storm assessments.
3. Apply photogrammetry software to evaluating the dune systems' effectiveness in reducing storm damage.
4. Develop targeted ecological restoration plans for high-priority sites.
5. Perform restoration actions to strengthen dune resilience.

The key to the project's success was using biomimicry techniques, installing wood matrices to create turbulence in the wind column and reduce wind velocity and facilitating uniform sand accumulation. The use of biomimicry matrices proved effective in protecting newly planted vegetation and enhancing dune stability against storm surges. The initiative also involved installing wooden boardwalks, adding educational signage, planting dune vegetation and installing wooden stakes as sand-trapping devices (Figure 0-16). These measures are intended to redirect foot traffic over sensitive dune habitats, increase public awareness about the importance of dune systems and enhance dune height and stability.



Figure 0-16: Sand-trapping devices used by Vida Marina (NOAA)

The project has garnered interest from students at various educational levels working to integrate practical on-site learning with ecological conservation. The involvement of student volunteers in restoration efforts not only contributes to students' educational requirements but also fosters a sense of stewardship and community engagement in Puerto Rico's environmental conservation endeavors.

Vida Marina's work illustrates the effectiveness of NNBS in coastal dune restoration, which offers a sustainable, cost-effective approach to enhancing shoreline resilience (Figure 0-17). The success of these methods demonstrates the potential for broader application of NNBS across Puerto Rico, which could contribute significantly to Puerto Rico's coastal management and environmental protection efforts aimed at working with nature instead of against it.

Following the success of this project, in 2023, FEMA obligated \$650,000 for a similar effort along segments of Middles Beach and Poza de Teodoro in Isabela, Finca Nolla in Hatillo, and Maranto Beach in Arecibo. The project included constructing 310 linear feet of boardwalks and 5,035 linear feet of exclusion fences and installing 21,830 biomimicry sand matrix units and 12 educational signs.



Figure 0-17: Top: pre-restoration, 2019; bottom: post-restoration, 2020. Before-and-after photos showing the success of Vida Marina’s work at Pedro Albizu Campos, Bajuras, Isabela (Vida Marina)

4.2. Protectores de Cuencas: Enhancing Coastal Resilience in Puerto Rico through Natural and Nature-Based Solutions

The second case study is Protectores de Cuencas: Enhancing Coastal Resilience in Puerto Rico through Natural and Nature-Based Solutions that took place from 2012 to 2017.¹¹ Protectores de Cuencas (PDC) is a nongovernmental organization (NGO) that restores and protects watersheds across Puerto Rico. The type of project and project partners are listed in Table 0-4.

¹¹ Protectores de Cuencas, “Implementation of the Guánica Bay Watershed Management Plan” (2018), https://www.ncei.noaa.gov/data/oceans/coris/library/NOAA/CRCP/NOS/OCM/Projects/397/ViqueiraRios2018_Guanica_Watershed_Management_Implementation.pdf.

Table 0-4: Protectores de Cuencas NNBS Case Study Project Type and Partners

Project Type	Partners
Coastal and wetland restoration	<ul style="list-style-type: none"> ▪ NOAA Marine Debris Program. ▪ Puerto Rico DNER. ▪ Local Community Leaders and Volunteers.

PDC has spearheaded pivotal environmental restoration efforts within the Guánica State Forest and Biosphere Reserve, particularly at *Playa La Jungla* and *Playa de Tamarindo*. These areas are known for their rich biodiversity, including federally protected sea turtles and the endangered Puerto Rican Crested Toad, but have faced significant challenges due to high visitor traffic, coastal erosion, habitat degradation, and the impact of extreme weather events. In response, PDC initiated a series of NNBS projects aimed at enhancing coastal resilience and restoring natural habitats.

The restoration strategies implemented by PDC include creating sand mounds and planting native vegetation to stabilize dunes and shorelines, effectively bolstering the area’s defense against erosion and storm surges (Figure 0-18). To minimize human impact on these sensitive ecosystems, access restriction measures such as bollards were installed, and boardwalks were constructed to provide environmentally friendly visitor access (Figure 0-19). Access to a seasonal lagoon and spawning ground for the endangered Puerto Rican crested toad (*Peltophryne lemur*) was permanently cordoned off to vehicles with bollards to avoid its use as a parking lot when dry.



Figure 0-18: Construction of sand mounds at Playa Tamarindo (Protectores de Cuencas, used with permission)



Figure 0-19: Boardwalk and access restriction installation at Playa La Jungla (Protectores de Cuencas, used with permission)

Key techniques employed in the restoration efforts are as follows:

- Creation of engineered sand mounds and planting of vegetation for dune and shoreline stabilization;
- Installation of access-restriction bollards to protect natural habitats;
- Construction of boardwalk to minimize visitor impact on the landscape;
- Repair of roadway with rock armoring and native plantings for coastal resilience;
- Conversion of impacted areas into critical habitats such as freshwater lagoons.

The success of these efforts is largely attributable to PDC’s holistic approach to ecological restoration, which integrates scientific methodologies with community insights and focuses on the preservation of natural habitats. By tailoring strategies to the environmental and geographical conditions of the area, PDC has demonstrated the effectiveness of NNBS in coastal restoration. The organization’s work not only contributes to the ecological health of La Jungla and Playa de Tamarindo but also serves as an educational platform, promoting environmental awareness and stewardship among the local community and volunteers involved in the restoration process.

PDC, alongside the NOAA Marine Debris Program, also launched the “Think Before You Drop It” campaign, a research-based social marketing initiative aimed at reducing litter on beaches through community cleanups, educational workshops and outreach strategies such as photography contests. The campaign highlights PDC’s innovative approach to engaging the community in conservation efforts and fostering a culture of environmental stewardship.

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